Beauty Physics at CERN

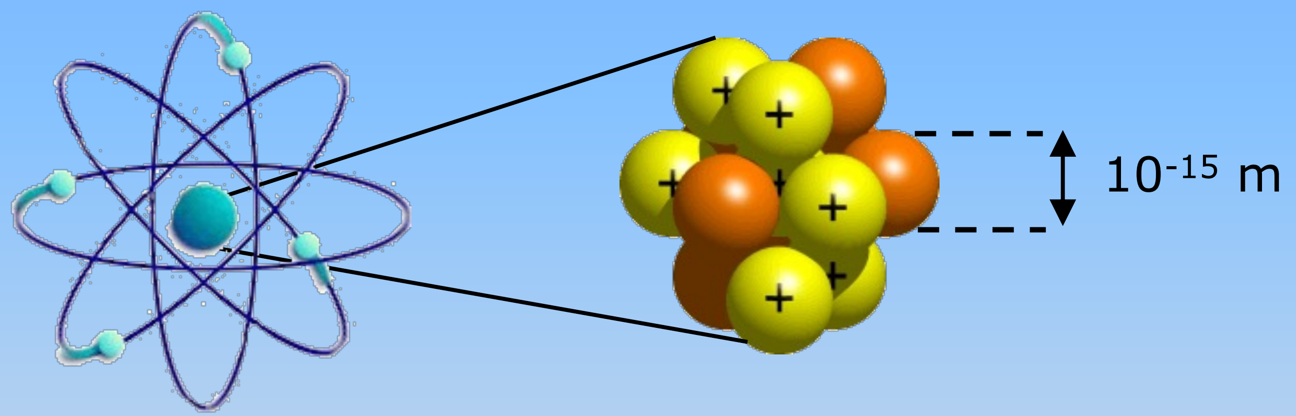
Teacher Programme, 13 Aug 2024

LHCb

- Why particle physics?
- Why LHCb?
- Results
- Higgs and LHCb

Particle Physics

Study Nature at small distances < 10^{-15} m

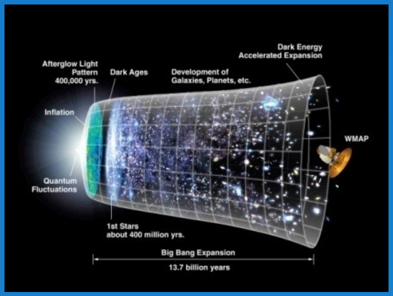


atom nucleus

Quantum theory describes phenomena down to 10^{-18} m

(Compare: 10^{+18} m = 100 lightyear)

Powers of ten …



Universe

10^{26} m

Milky way

10^{21} m

Solar system

10^{13} m

Earth

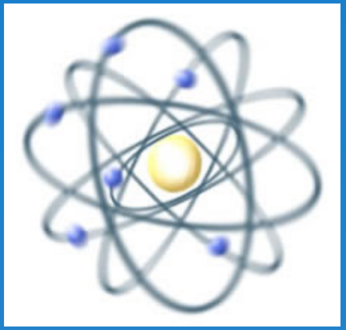
10^{7} m

Spider

10^{-2} m

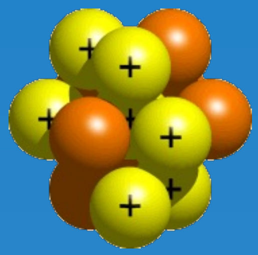
Atom

10^{-10} m



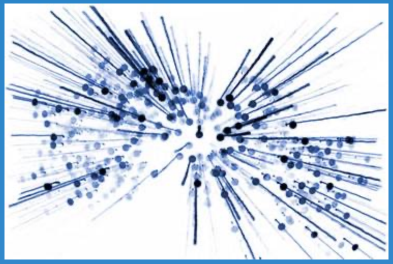
Nucleus

10^{-15} m

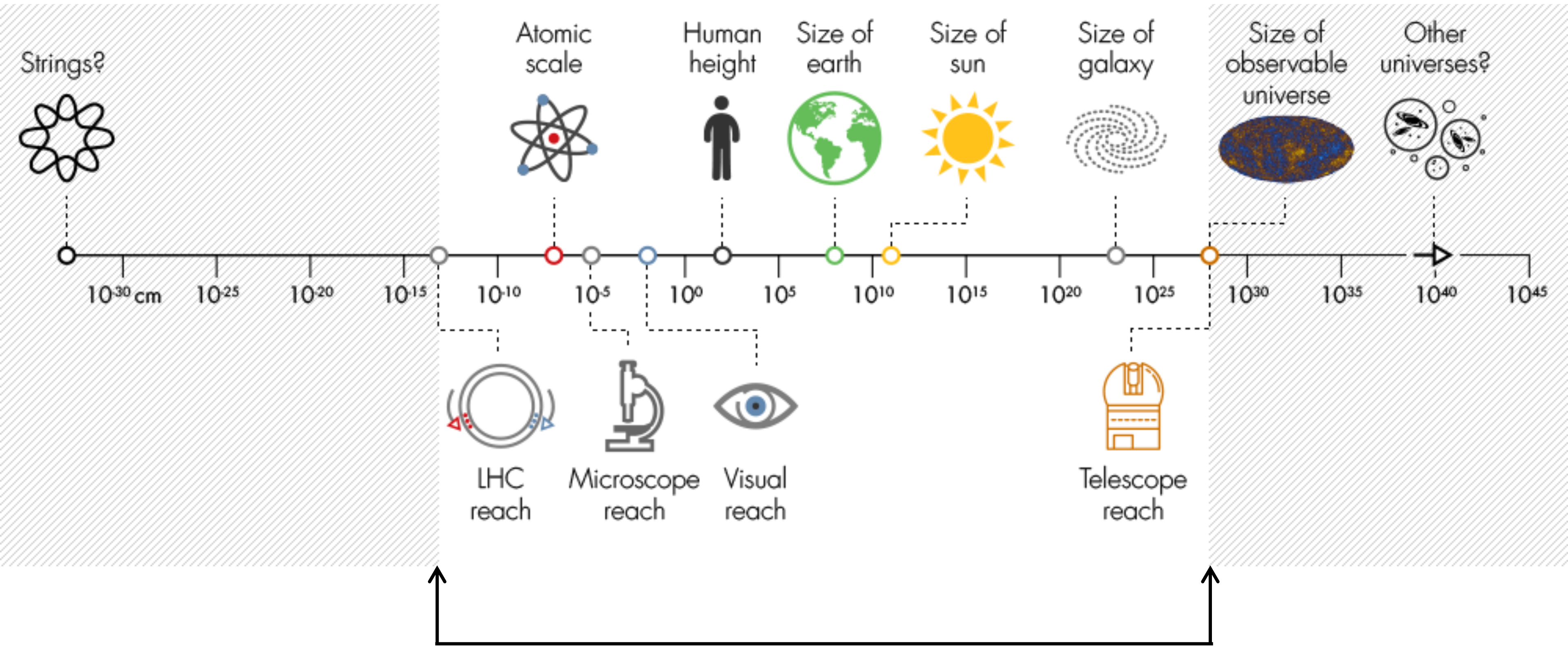


Collissions

10^{-18} m

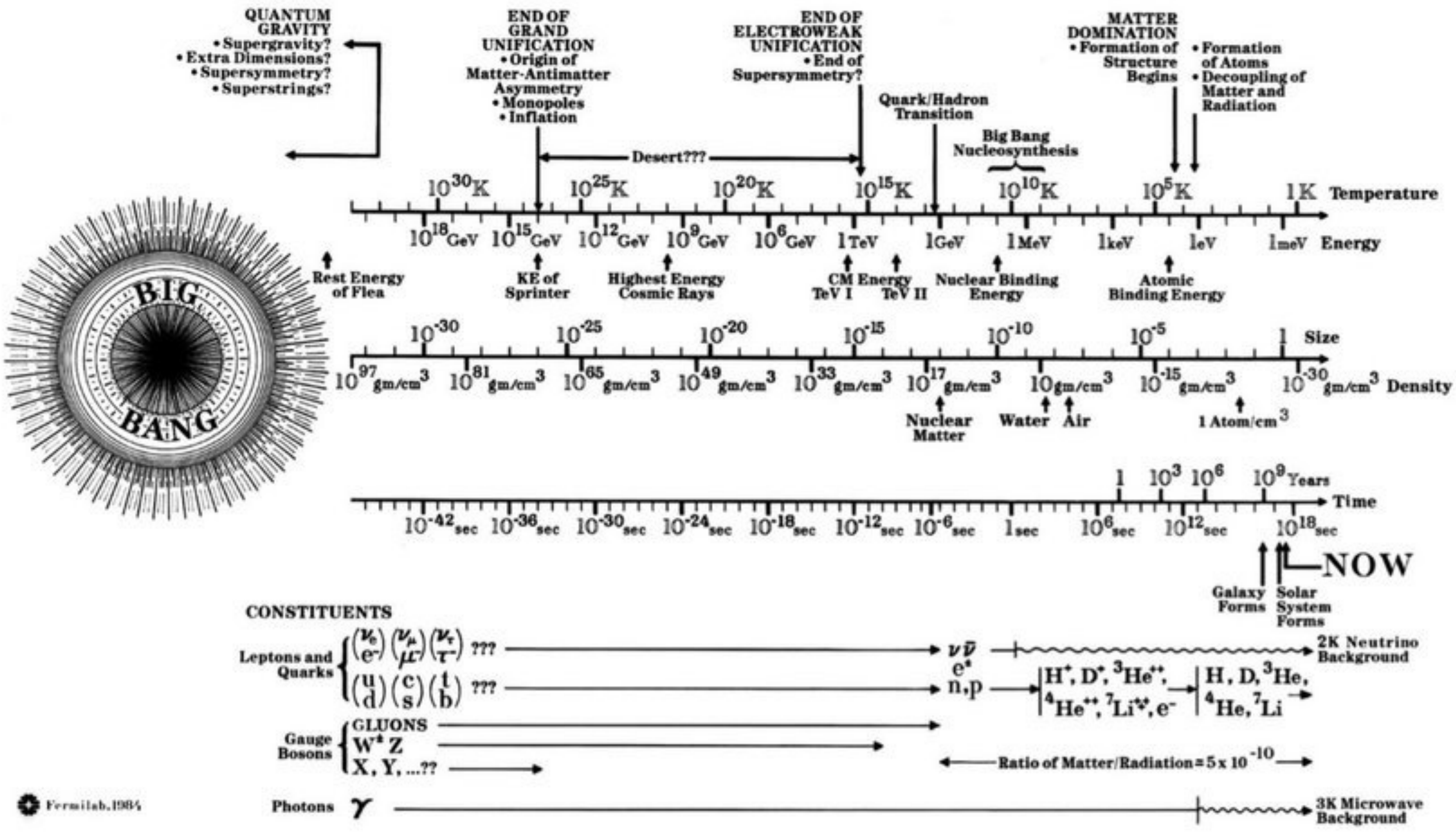


Scale



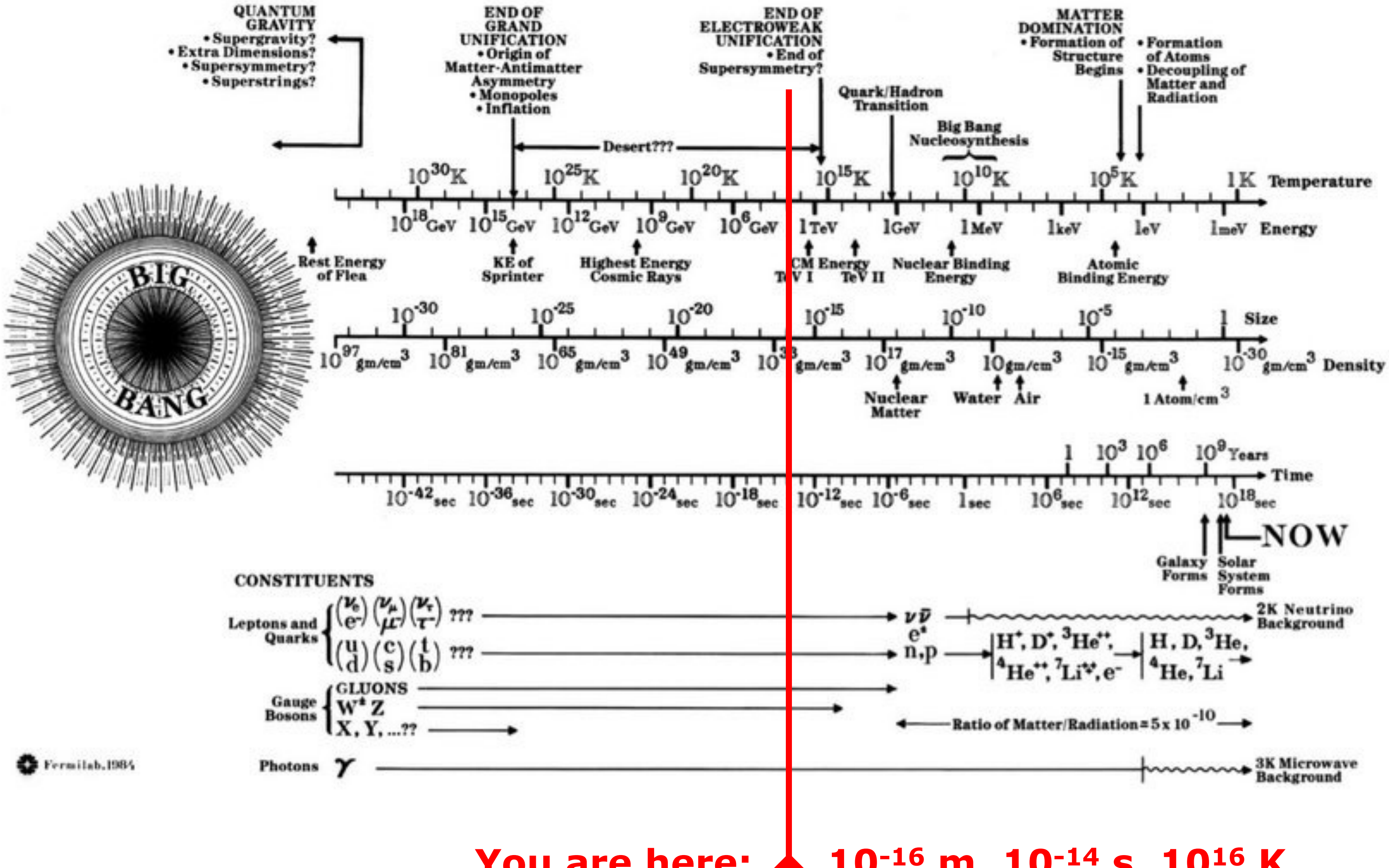
- LHC
- CMB

Complete History of the Universe



•https://www.researchgate.net/publication/357823952/figure/fig1/AS:1111988524589069@1642130132503/Complete-history-of-the-Universe-a-collaboration-of-Angela-Gonzalez-of-Fermilab-and-the.jpg

Complete History of the Universe



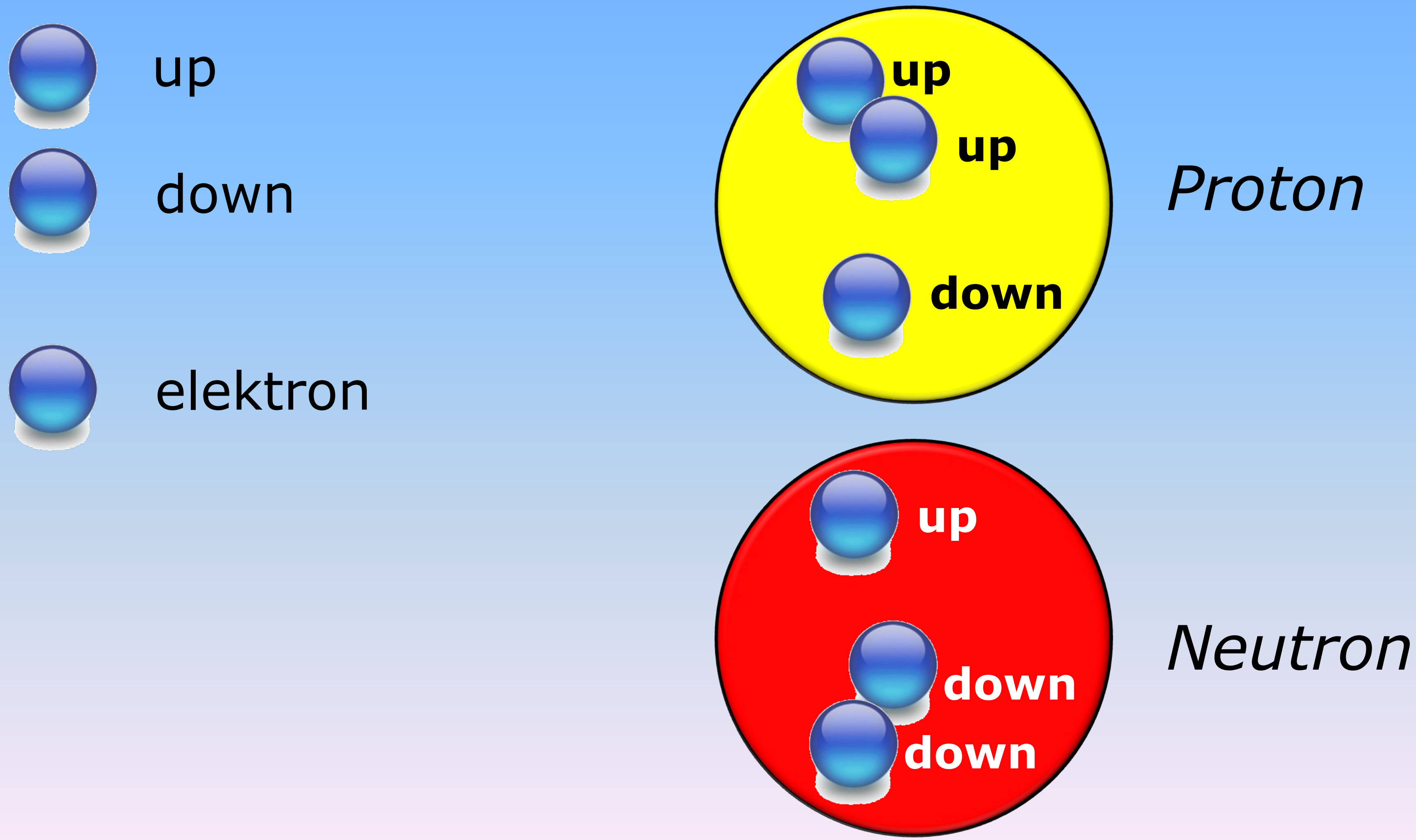
You are here: ◆ 10^{-16} m, 10^{-14} s, 10^{16} K

• https://www.researchgate.net/publication/357823952/figure/fig1/AS:1111988524589069@1642130132503/Complete-history-of-the-Universe-a-collaboration-of-Angela-Gonzalez-of-Fermilab-and-the.jpg

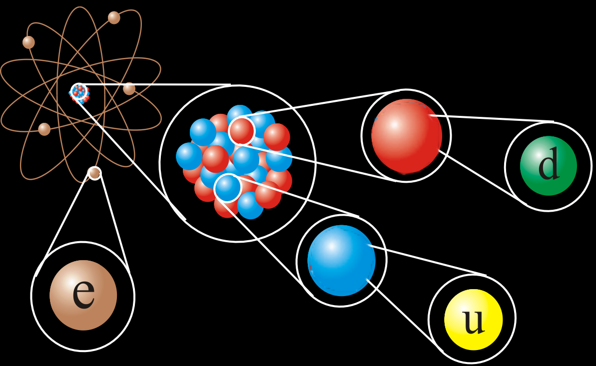
State of affairs in 2024

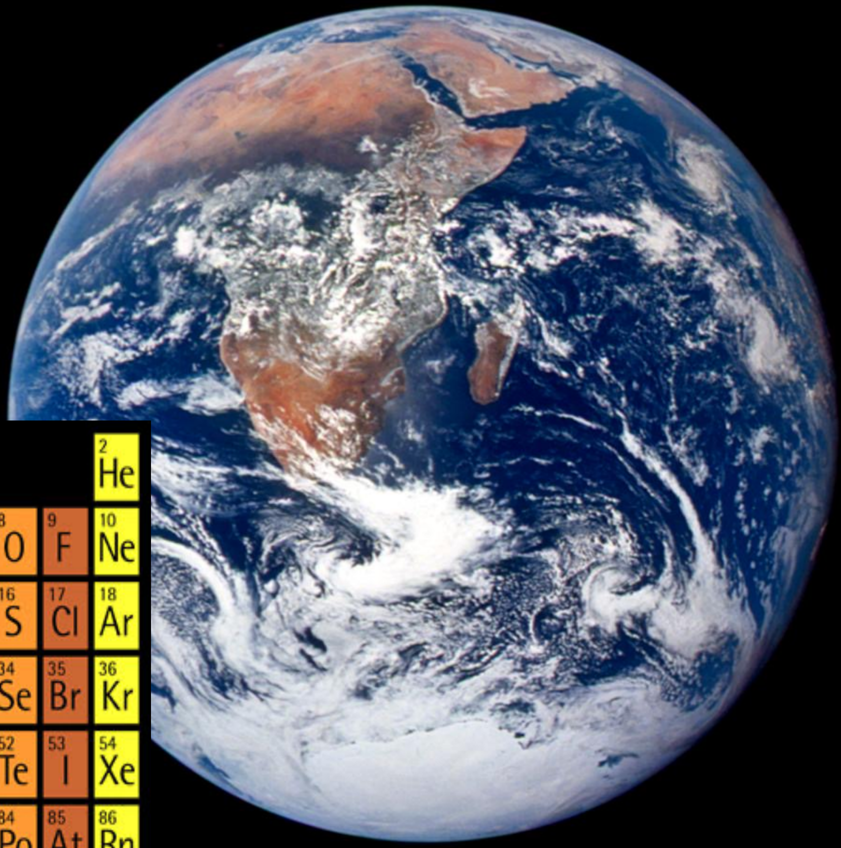
http:// pdg.lbl.gov

The elementary particles

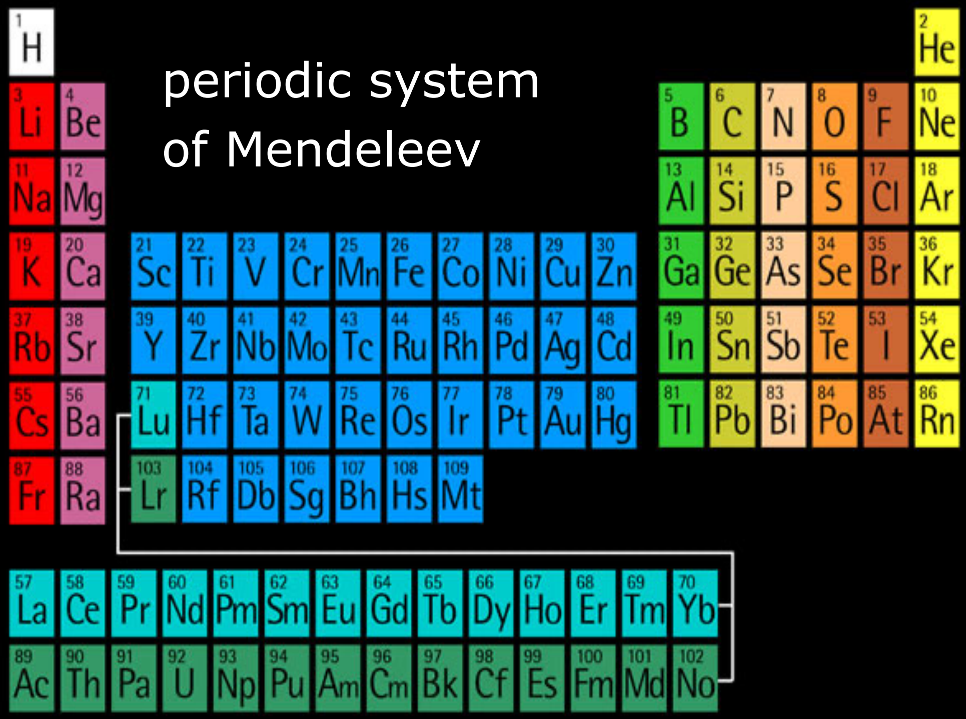


What can one construct of these 3 building blocks?





periodic system
of Mendeleev

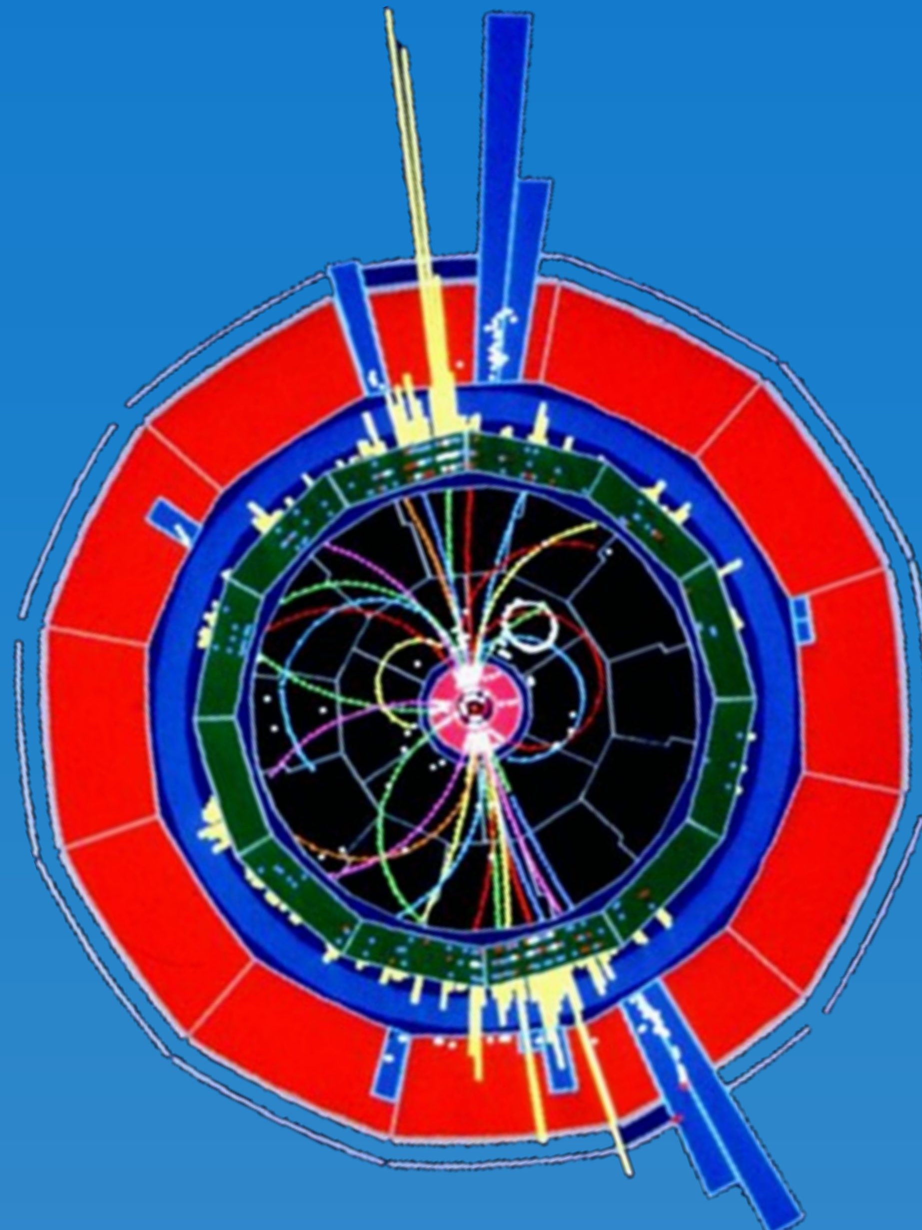


Everything!

Elementary Particles

Not one series, but three!

	I	II	III
quarks	u	c (1976)	t (1995)
	d	s (1947)	b (1978)
leptons	e (1895)	□ (1936)	τ (1973)
	ν_e (1956)	ν□ (1963)	ν_τ (2000)

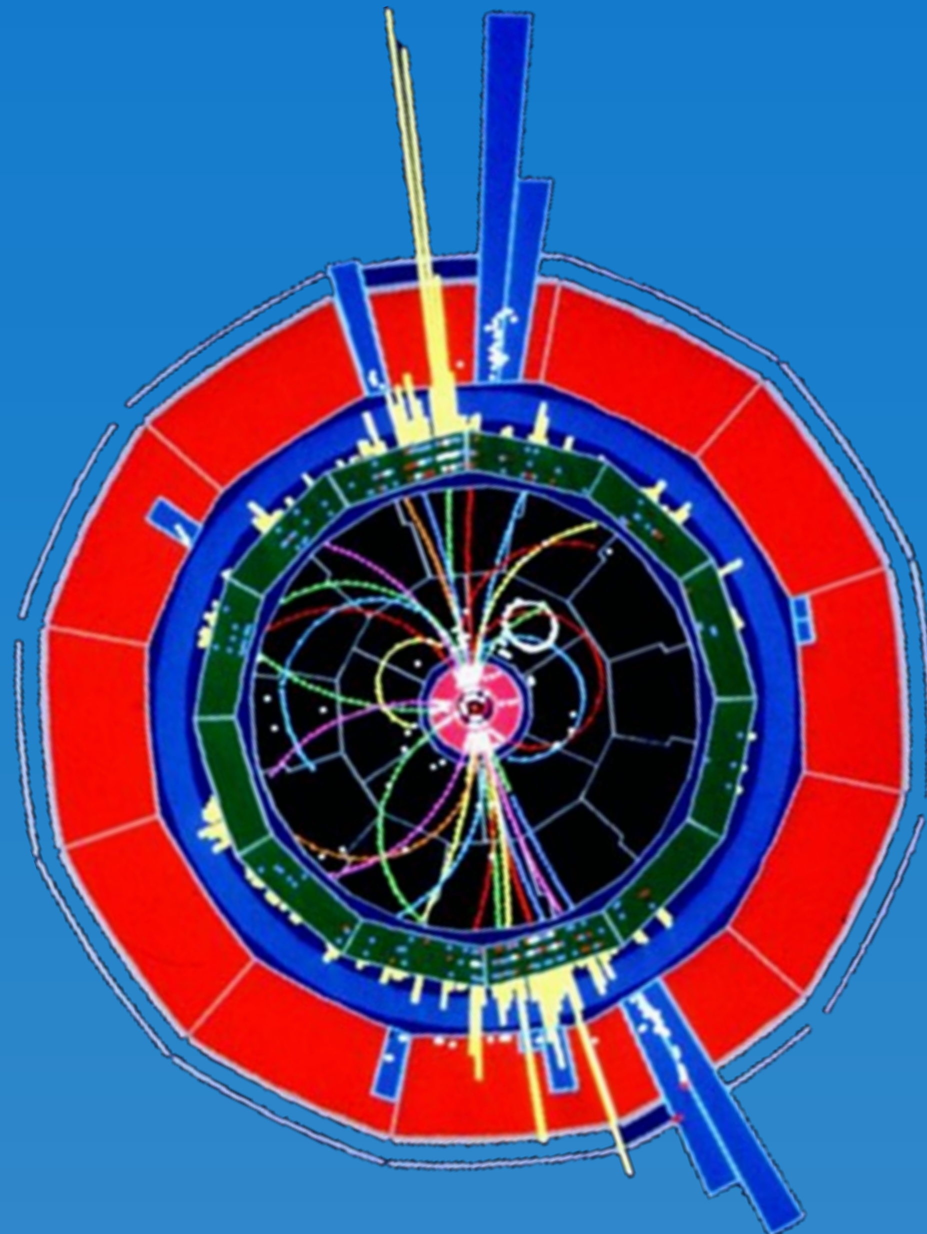


Elementary Particles

Generation:

	I	II	III	Charge
quarks	u	c *(1976)*	t *(1995)*	+2/3 e
	d	s *(1947)*	b *(1978)*	-1/3 e
leptons	e *(1895)*	□ *(1936)*	τ *(1973)*	-1 e
	ν_e *(1956)*	ν□ *(1963)*	ν_τ *(2000)*	0 e

Matter

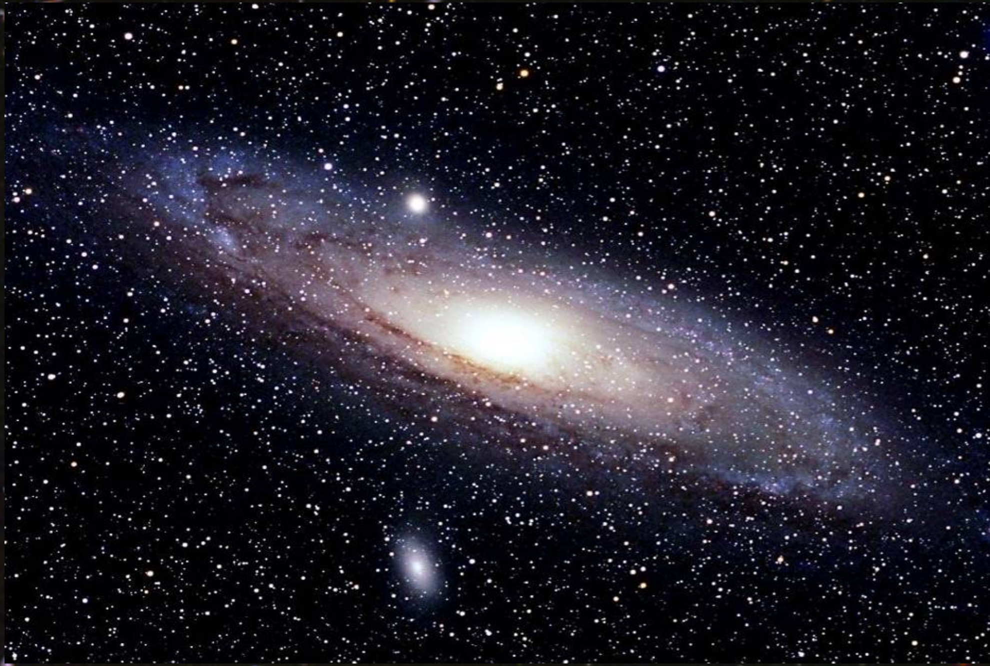


Is this all?

Generation:

	I	II	III	Charge
quarks	u	c (1976)	t (1995)	+2/3 e
	d	s (1947)	b (1978)	-1/3 e
leptons	e (1895)	□ (1936)	τ (1973)	-1 e
	ν_e (1956)	$\nu_□$ (1963)	ν_τ (2000)	0 e

Matter



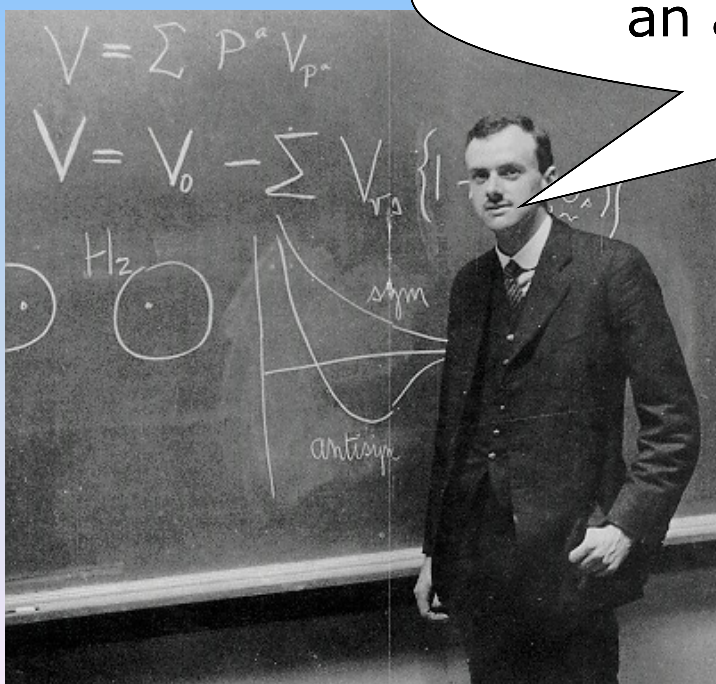
Anti-matter

Revolutions previous century:

- Theory of relativity
- Quantum Mechanics

Paul Dirac (1928): relativistic quantum theory!

For each matter particle there is an anti-matter particle



Anti-matter particles:

- Same mass
- Opposite charge

Elementary particles

	I	II	III	Charge
quarks	**u**	**c** (1976)	**t** (1995)	+2/3 e
	d	**s** (1947)	**b** (1978)	-1/3 e
leptons	**e** (1895)	□ (1936)	τ (1973)	-1 e
	ν_e (1956)	$\nu_{□}$ (1963)	ν_τ (2000)	0 e

Matter

Elementary particles

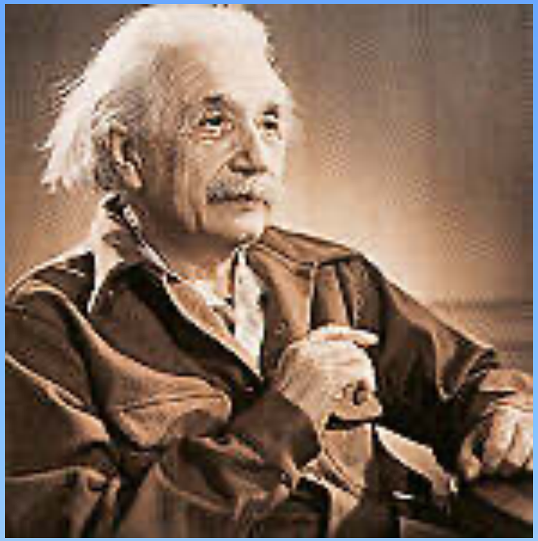
Matter

	I	II	III	Charge
quarks	**u**	**c** (1976)	**t** (1995)	+2/3 e
	d	**s** (1947)	**b** (1978)	-1/3 e
leptons	**e** (1895)	**□** (1936)	**τ** (1973)	-1 e
	ν_e (1956)	$\nu_□$ (1963)	ν_τ (2000)	0 e

Anti-matter

Charge	I	II	III
-2/3 e	$\bar{u}$	$\bar{c}$	$\bar{t}$
+1/3 e	$\bar{d}$	$\bar{s}$	$\bar{b}$
+1 e	$\bar{e}$	$\bar{□}$	$\bar{\tau}$
0 e	$\bar{\nu}_e$	$\bar{\nu}_□$	$\bar{\nu}_\tau$

How do you make anti-matter??

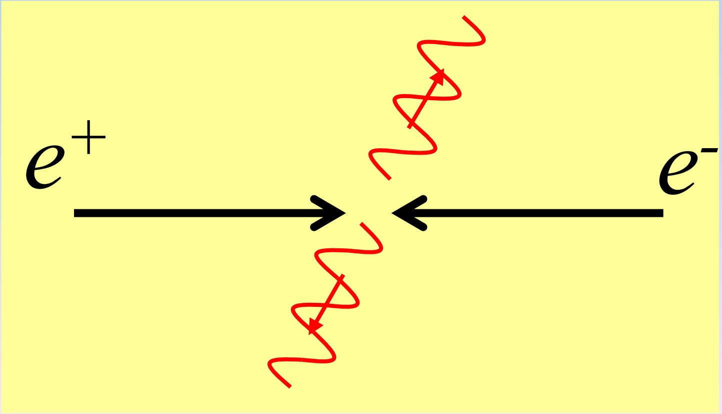


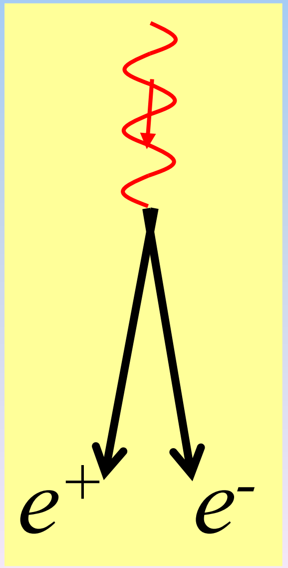
Albert Einstein:

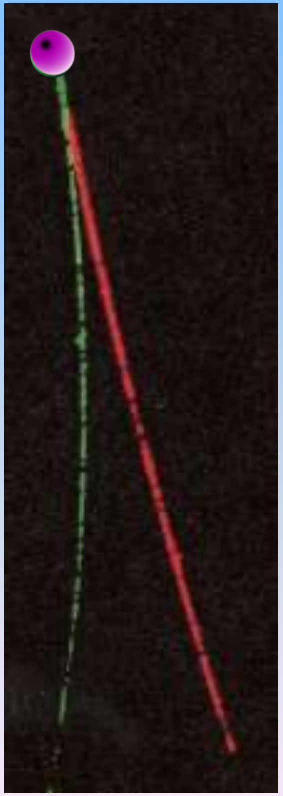
$E=mc^2$

matter + antimatter = light !

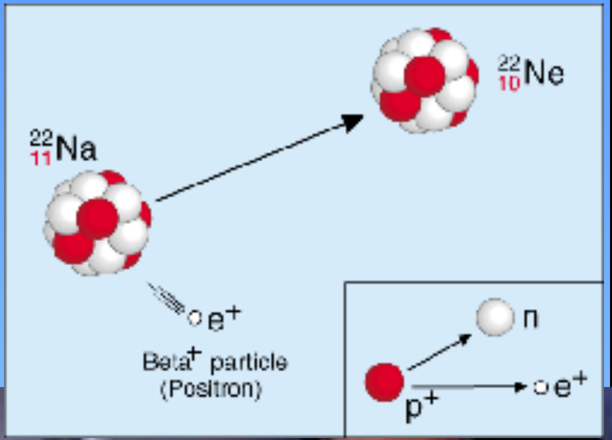
(and vice versa)

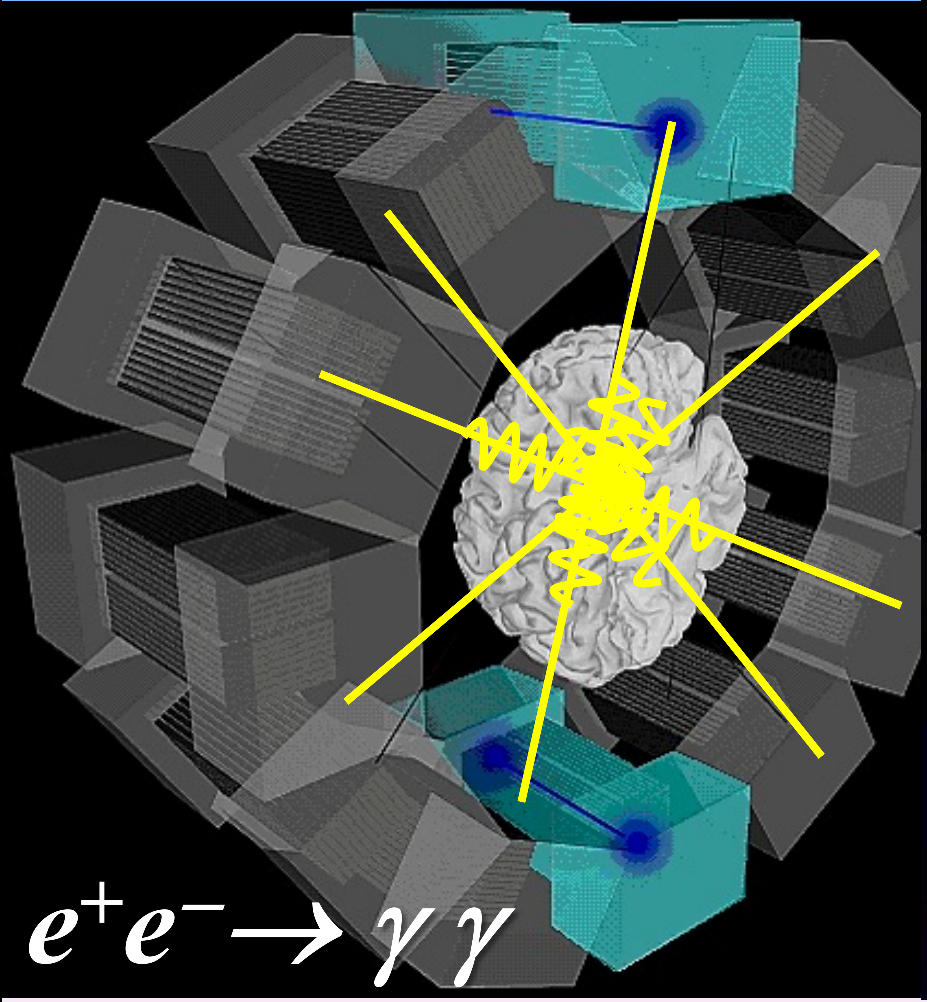






Anti-matter in hospitals: the PET-scan



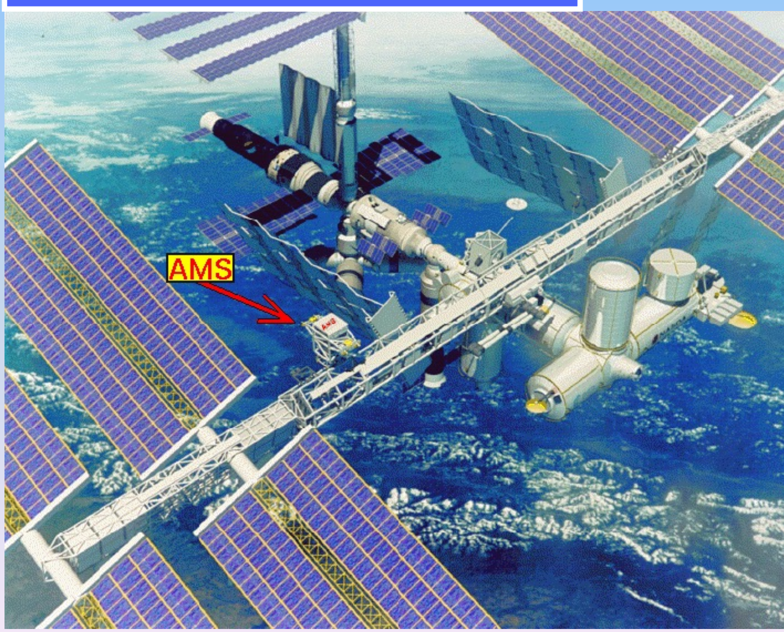


What is yet unknown:

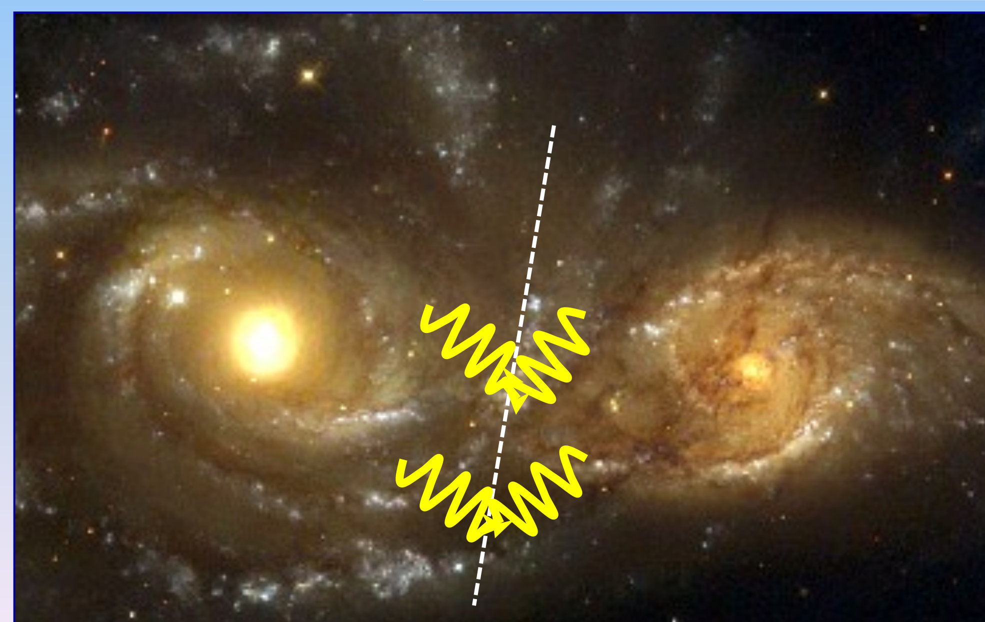
I. What is yet unknown? "*Anti-matter*"

Where did the anti-matter go?

No anit-matter with satellites



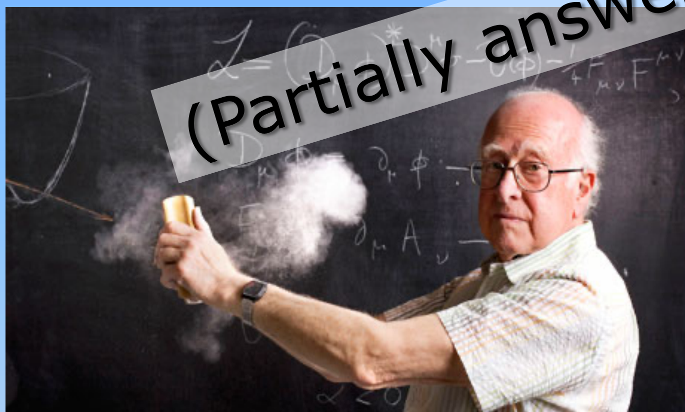
No anti-matter galaxies

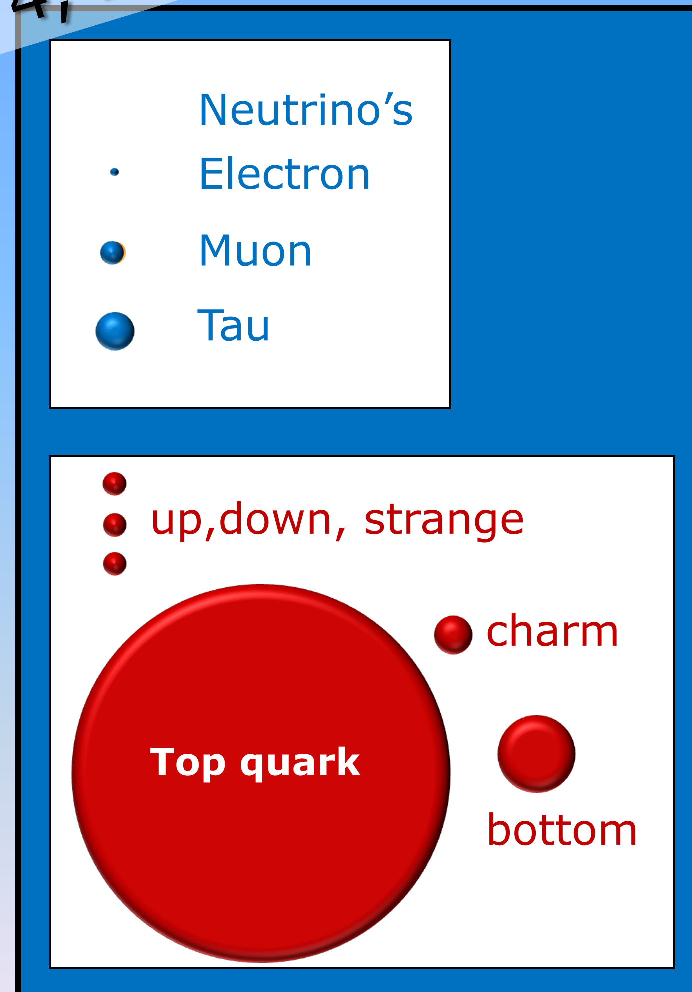


II. What is yet unknown? "*Higgs*"

(Partially answered on July 4, 2012 !)

Mass of particles

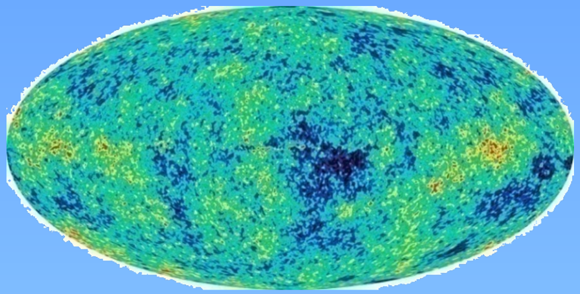




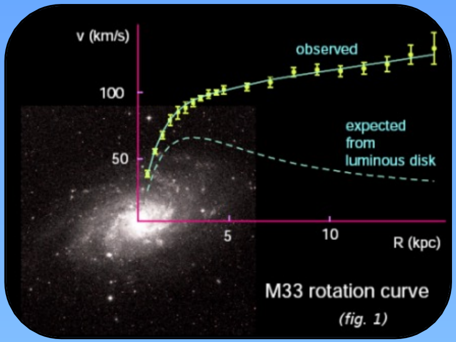
Curious prediction:

The Higgs boson:
ensures that particles have mass in the theory

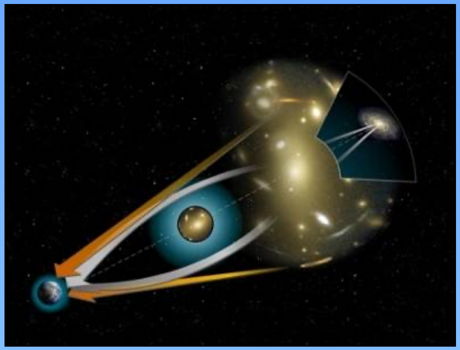
III. What is yet unknown? *"Dark matter"*



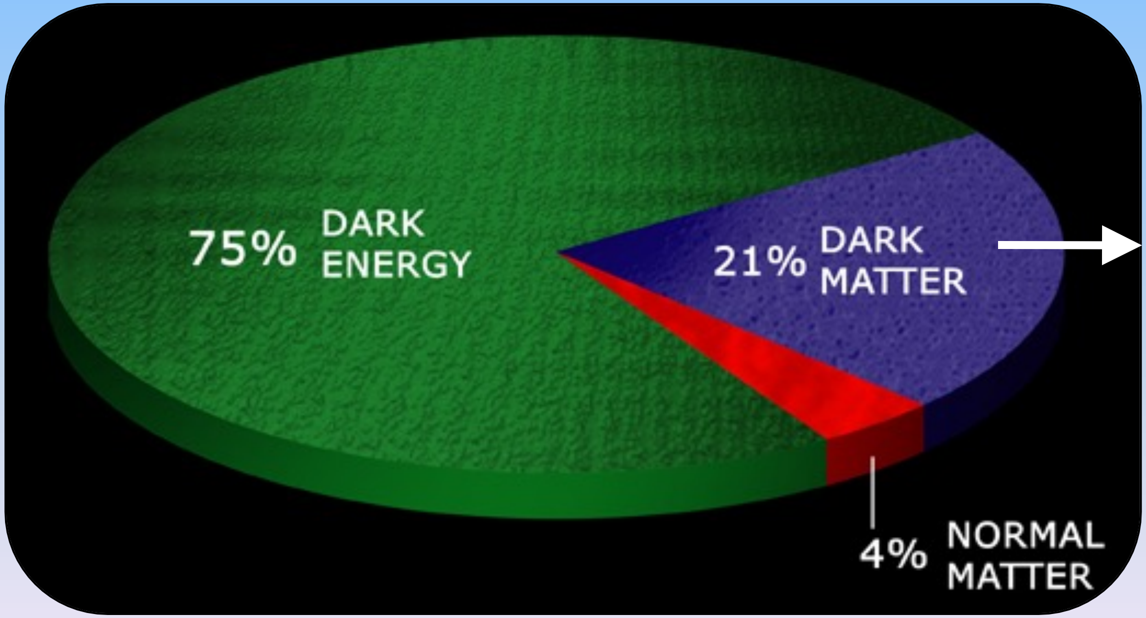
Temperature fluctuations



Rotation-curves



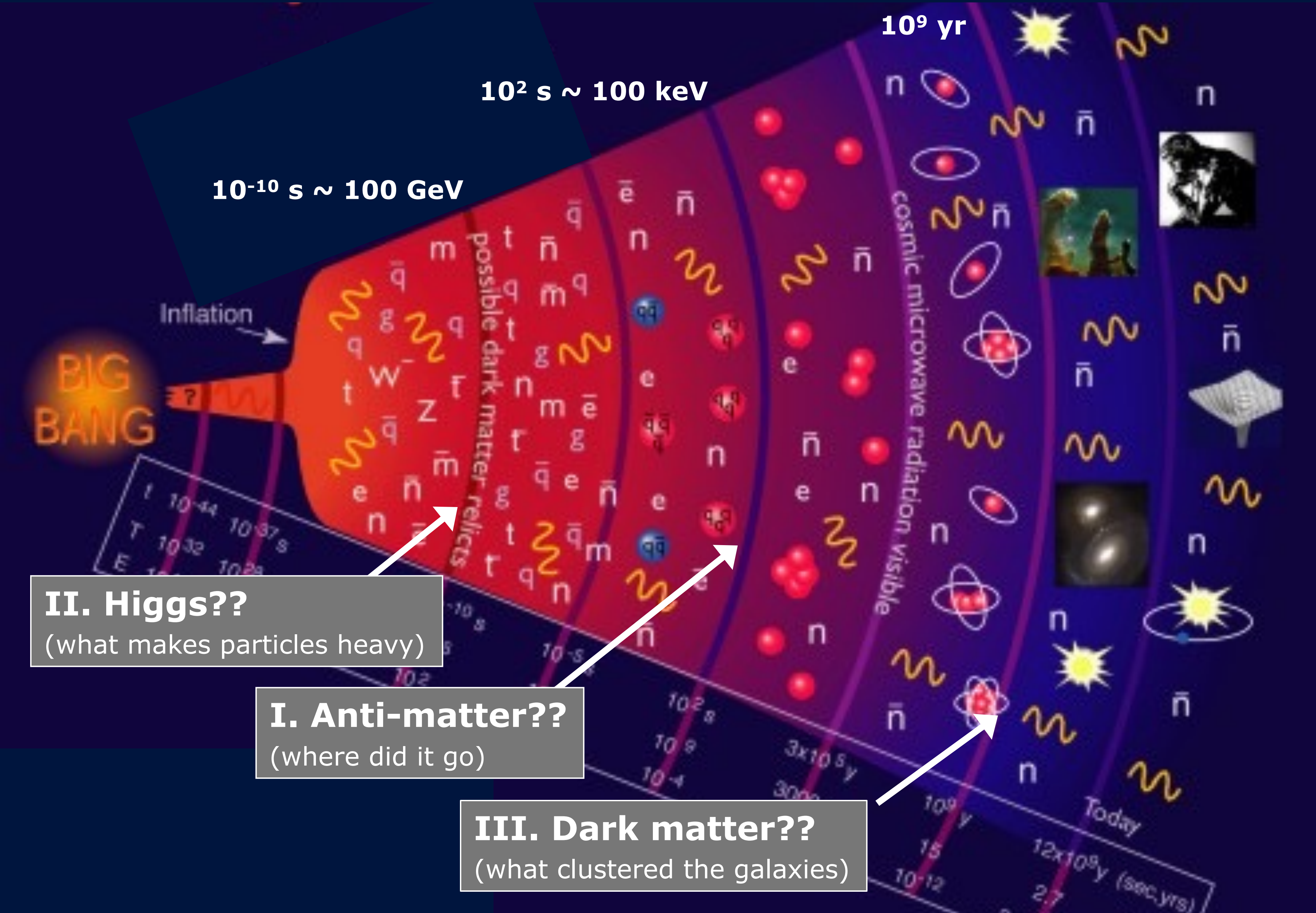
Gravitational lens

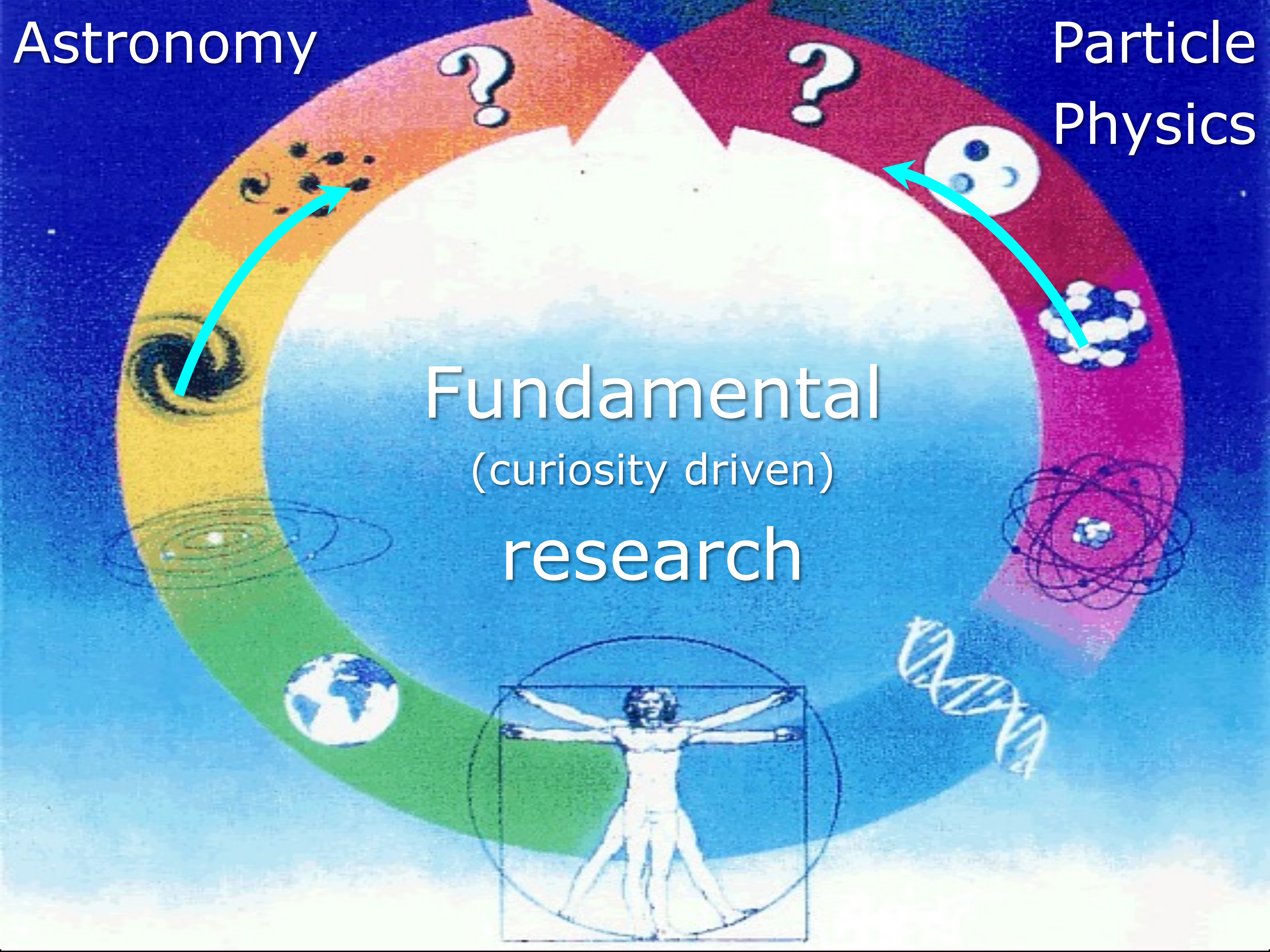


What is dark matter?

We only studied 4% of the content of the Universe...!

What is yet unknown? Three Big Questions




Astronomy
Particle Physics
Fundamental
(curiosity driven)
research

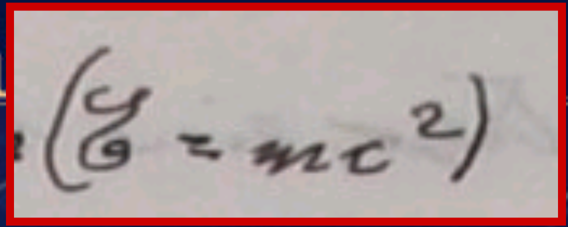
Classical collissions

Quantum mechanical collissions

What do you expect?

$$
\begin{aligned}
&-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
&\tfrac{1}{2}ig_s^2(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
&M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \\
&\tfrac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+\phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \tfrac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\tfrac{2M^2}{g^2} + \\
&\tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - \\
&W^-_\nu \partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - \\
&W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
&\tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
&g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \\
&\tfrac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - \\
&gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - \\
&W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \tfrac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \\
&\phi^+\partial_\mu H)] + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + \\
&igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + \\
&igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \\
&\tfrac{1}{4}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + \\
&W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
&W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - \\
&g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j - \\
&\bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \\
&\tfrac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - \\
&1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + \\
&(\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1 + \\
&\gamma^5)u^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}\tfrac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \\
&\tfrac{g}{2}\tfrac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + \\
&m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1 - \\
&\gamma^5)u^\kappa_j] - \tfrac{g}{2}\tfrac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2}\tfrac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \\
&\tfrac{ig}{2}\tfrac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \\
&\tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \\
&\partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \\
&\partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \\
&\partial_\mu\bar{X}^- X^-) - \tfrac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2}\bar{X}^0 X^0 H] + \\
&\tfrac{1-2c_w^2}{2c_w}igM[\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-] + \tfrac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \\
&igMs_w[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \tfrac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]
\end{aligned}
$$

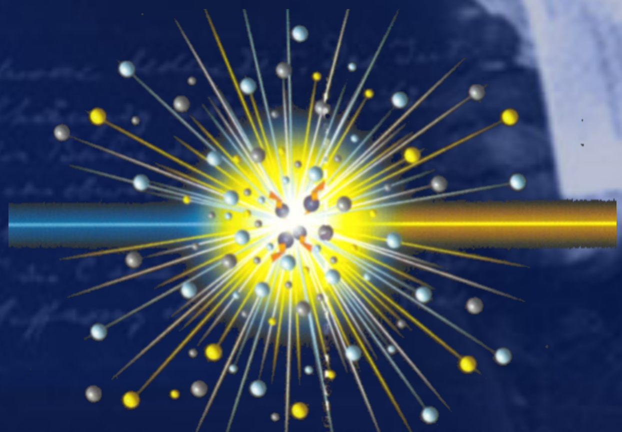
Precise mathematical predictions exist for 40 years!

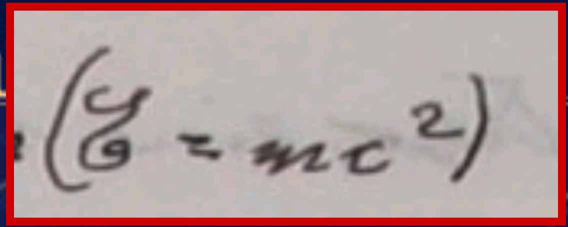


How do we discover new particles?

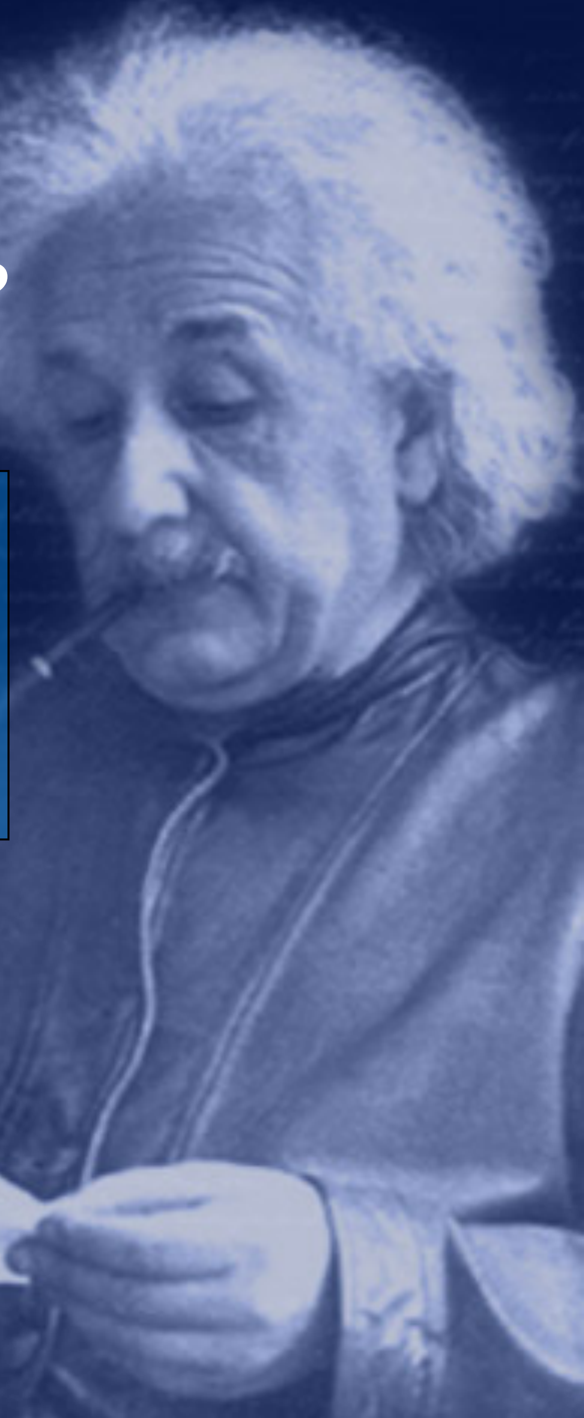
With the LHC at CERN:

1) Transform energy into matter!





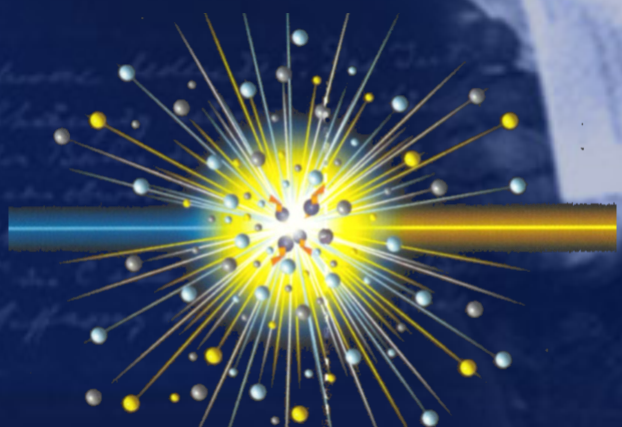
How do we discover new particles?



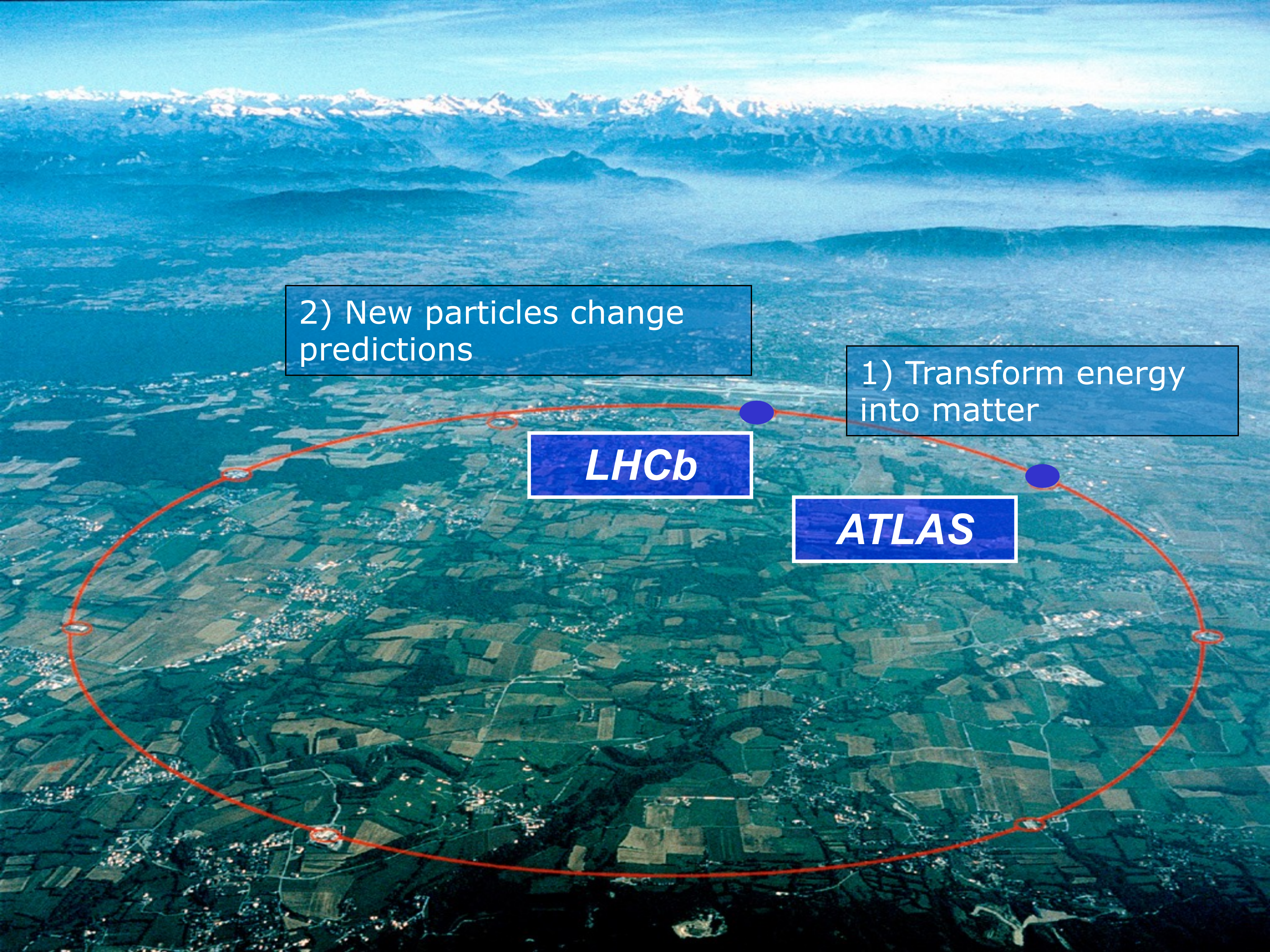
With the LHC at CERN:

1) Transform energy into matter!

2) New particles change predictions

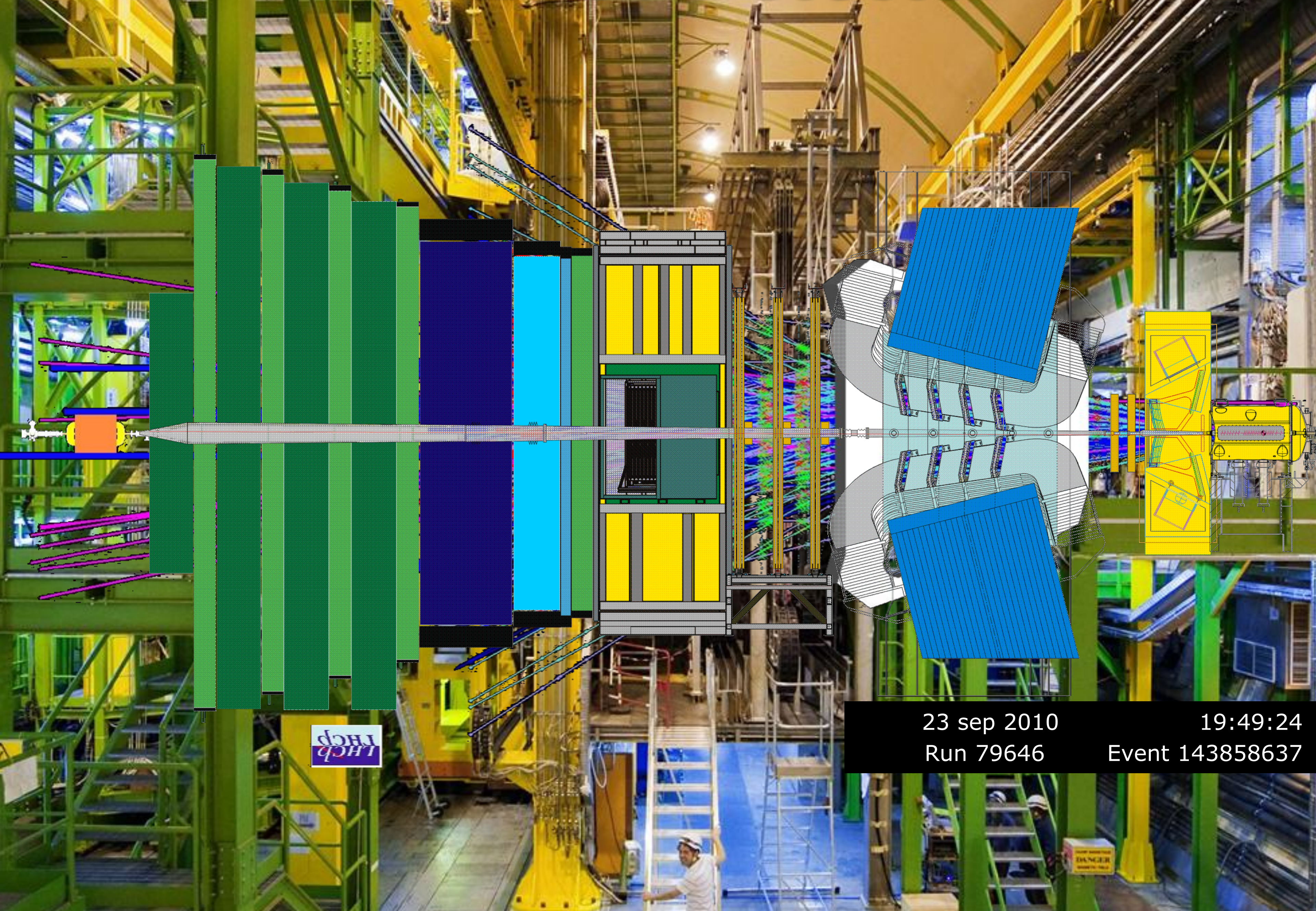



LHCb
ATLAS
CMS
ALICE



2) New particles change predictions
1) Transform energy into matter
LHCb
ATLAS

The LHCb Detector



$$
\begin{gathered}
-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g^2_s f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
\frac{1}{2} i g^2_s (\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c^2_w} M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \\
\frac{1}{2} m^2_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c^2_w} M \phi^0 \phi^0 - \beta_h [\frac{2M^2}{g^2} + \\
\frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-)] + \frac{2M^4}{g^2}\alpha_h - i g c_w [\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - \\
W^-_\nu \partial_\nu W^+_\mu)] - i g s_w [\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - \\
W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \frac{1}{2} g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
\frac{1}{2} g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c^2_w (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
g^2 s^2_w (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w [A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2 A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha [H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \\
\frac{1}{8} g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2 \phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2] - \\
g M W^+_\mu W^-_\mu H - \frac{1}{2} g \frac{M}{c^2_w} Z^0_\mu Z^0_\mu H - \frac{1}{2} i g [W^+_\mu (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - \\
W^-_\mu (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \frac{1}{2} g [W^+_\mu (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W^-_\mu (H \partial_\mu \phi^+ - \\
\phi^+ \partial_\mu H)] + \frac{1}{2} g \frac{1}{c_w} (Z^0_\mu (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - i g \frac{s^2_w}{c_w} M Z^0_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) + \\
i g s_w M A_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) - i g \frac{1-2c^2_w}{2c_w} Z^0_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + \\
i g s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{4} g^2 W^+_\mu W^-_\mu [H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \\
\frac{1}{4} g^2 \frac{1}{c^2_w} Z^0_\mu Z^0_\mu [H^2 + (\phi^0)^2 + 2(2s^2_w - 1)^2 \phi^+\phi^-] - \frac{1}{2} g^2 \frac{s^2_w}{c_w} Z^0_\mu \phi^0 (W^+_\mu \phi^- + \\
W^-_\mu \phi^+) - \frac{1}{2} i g^2 \frac{s^2_w}{c_w} Z^0_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) + \frac{1}{2} g^2 s_w A_\mu \phi^0 (W^+_\mu \phi^- + \\
W^-_\mu \phi^+) + \frac{1}{2} i g^2 s_w A_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) - g^2 \frac{s_w}{c_w} (2c^2_w - 1) Z^0_\mu A_\mu \phi^+ \phi^- - \\
g^1 s^2_w A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma\partial + m^\lambda_e) e^\lambda - \bar{\nu}^\lambda \gamma\partial \nu^\lambda - \bar{u}^\lambda_j (\gamma\partial + m^\lambda_u) u^\lambda_j - \\
\bar{d}^\lambda_j (\gamma\partial + m^\lambda_d) d^\lambda_j + i g s_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j \gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j \gamma^\mu d^\lambda_j)] + \\
\frac{ig}{4c_w} Z^0_\mu [(\bar{\nu}^\lambda \gamma^\mu (1+\gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s^2_w - 1 - \gamma^5) e^\lambda) + (\bar{u}^\lambda_j \gamma^\mu (\frac{4}{3} s^2_w - \\
1 - \gamma^5) u^\lambda_j) + (\bar{d}^\lambda_j \gamma^\mu (1 - \frac{8}{3} s^2_w - \gamma^5) d^\lambda_j)] + \frac{ig}{2\sqrt{2}} W^+_\mu [(\bar{\nu}^\lambda \gamma^\mu (1+\gamma^5) e^\lambda) + \\
(\bar{u}^\lambda_j \gamma^\mu (1+\gamma^5) C_{\lambda\kappa} d^\kappa_j)] + \frac{ig}{2\sqrt{2}} W^-_\mu [(\bar{e}^\lambda \gamma^\mu (1+\gamma^5) \nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa} \gamma^\mu (1 + \\
\gamma^5) u^\lambda_j)] + \frac{ig}{2\sqrt{2}} \frac{m^\lambda_e}{M} [-\phi^+ (\bar{\nu}^\lambda (1-\gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1+\gamma^5) \nu^\lambda)] - \\
\frac{g}{2} \frac{m^\lambda_e}{M} [H (\bar{e}^\lambda e^\lambda) + i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}} \phi^+ [-m^\kappa_d (\bar{u}^\lambda_j C_{\lambda\kappa} (1-\gamma^5) d^\kappa_j) + \\
m^\lambda_u (\bar{u}^\lambda_j C_{\lambda\kappa} (1+\gamma^5) d^\kappa_j] + \frac{ig}{2M\sqrt{2}} \phi^- [m^\lambda_d (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1+\gamma^5) u^\kappa_j) - m^\kappa_u (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1 - \\
\gamma^5) u^\kappa_j] - \frac{g}{2} \frac{m^\lambda_u}{M} H (\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2} \frac{m^\lambda_d}{M} H (\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2} \frac{m^\lambda_u}{M} \phi^0 (\bar{u}^\lambda_j \gamma^5 u^\lambda_j) - \\
\frac{ig}{2} \frac{m^\lambda_d}{M} \phi^0 (\bar{d}^\lambda_j \gamma^5 d^\lambda_j) + \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \\
\frac{M^2}{c^2_w}) X^0 + \bar{Y} \partial^2 Y + i g c_w W^+_\mu (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + i g s_w W^+_\mu (\partial_\mu \bar{Y} X^- - \\
\partial_\mu \bar{X}^+ Y) + i g c_w W^-_\mu (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + i g s_w W^-_\mu (\partial_\mu \bar{X}^- Y - \\
\partial_\mu \bar{Y} X^+) + i g c_w Z^0_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + i g s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \\
\partial_\mu \bar{X}^- X^-) - \frac{1}{2} g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c^2_w} \bar{X}^0 X^0 H] + \\
\frac{1-2c^2_w}{2c_w} i g M [\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} i g M [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \\
i g M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2} i g M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
\end{gathered}
$$

Quantum mechanical collissions

LHCb in numbers

~100,000 B events per sec

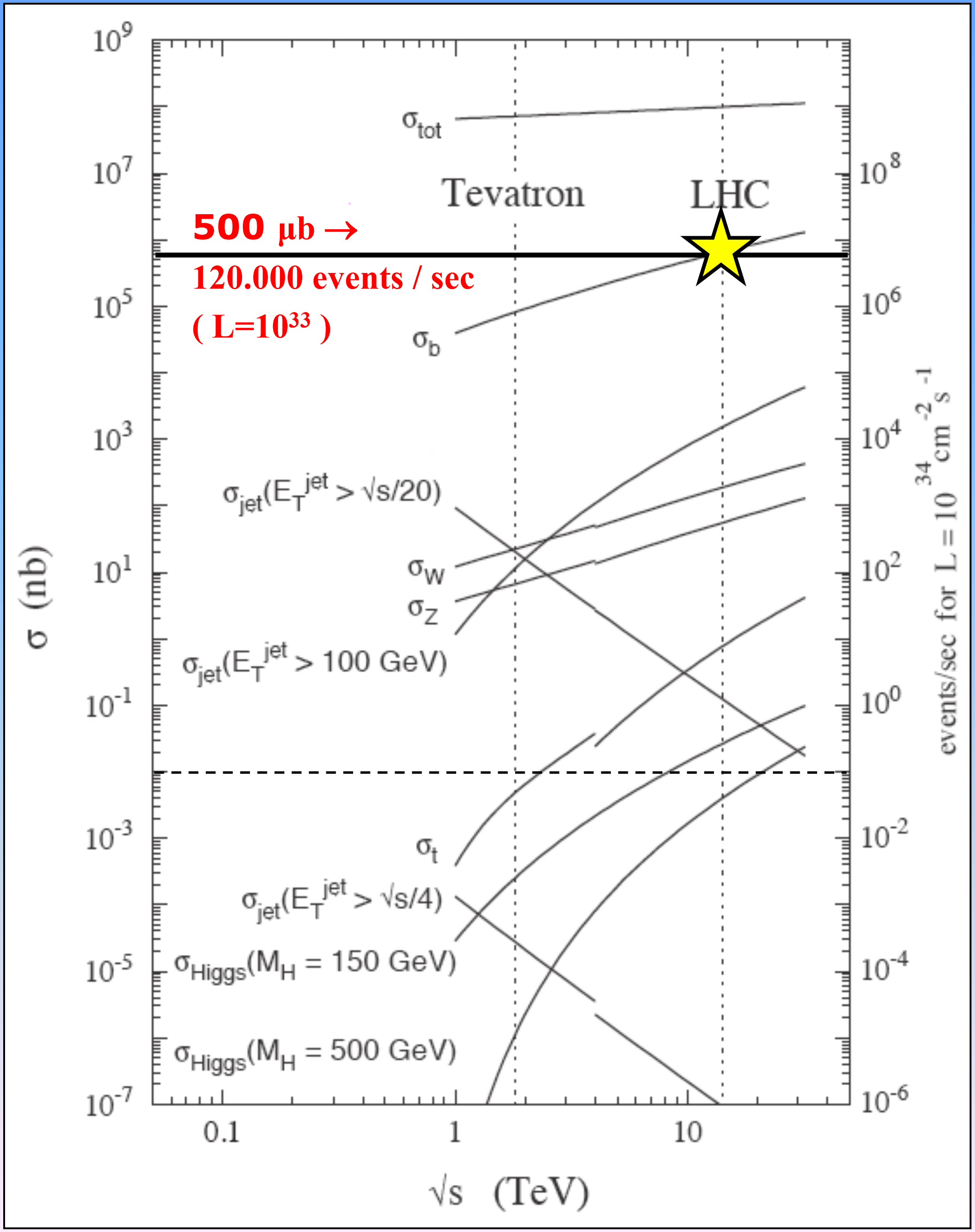
(compare: in ATLAS : 1 Higgs in 100 sec)

10^{11} B events per year

(compare: Babar has in total 10^9 B events)

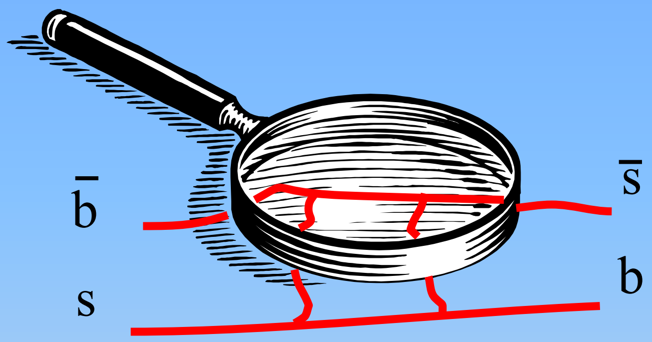
5 kHz to tape

(compare: ATLAS writes 200 Hz)

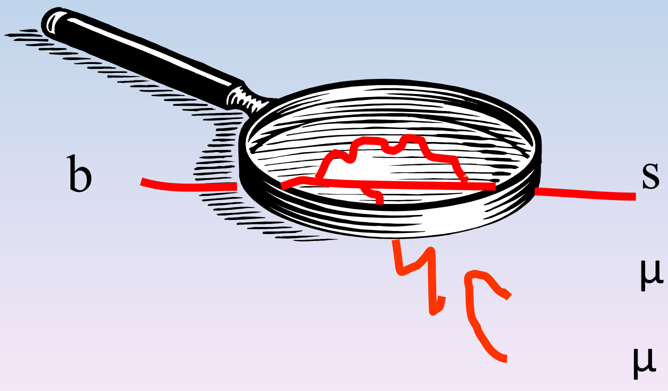


LHCb: study the *B* particle

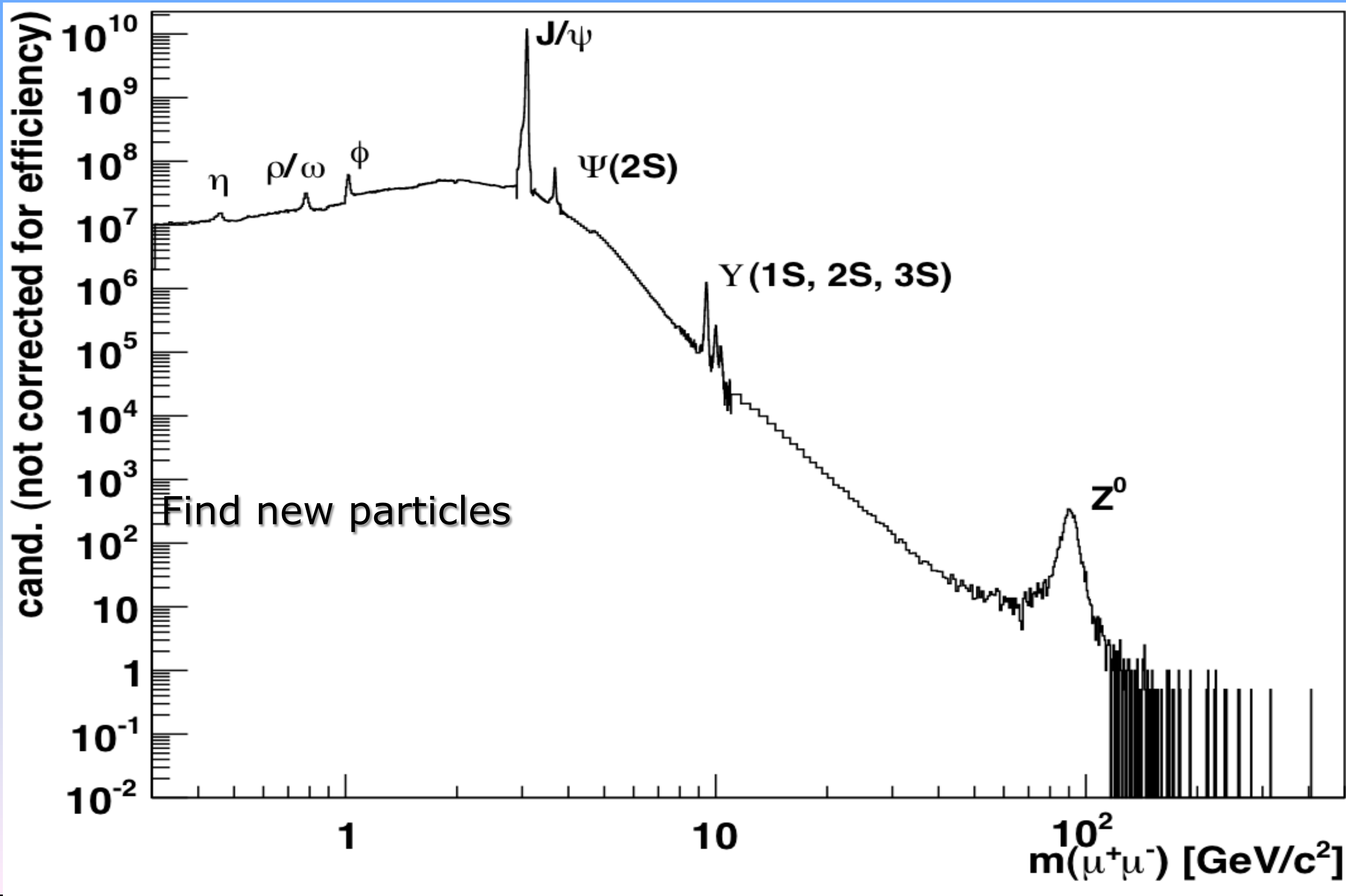
1) Find differences between matter and anti-matter



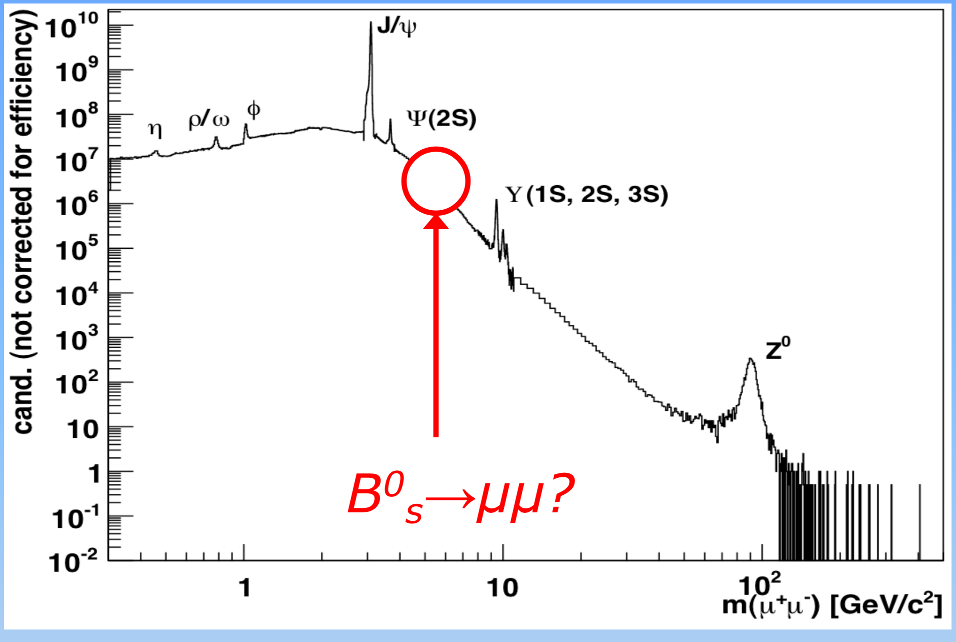
2) Find new particles



LHCb: study the *B* particle

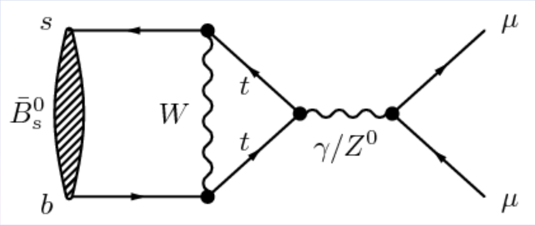


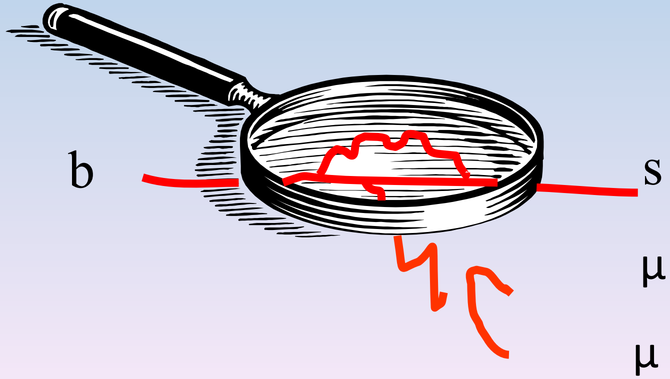
LHCb: study the *B* particle



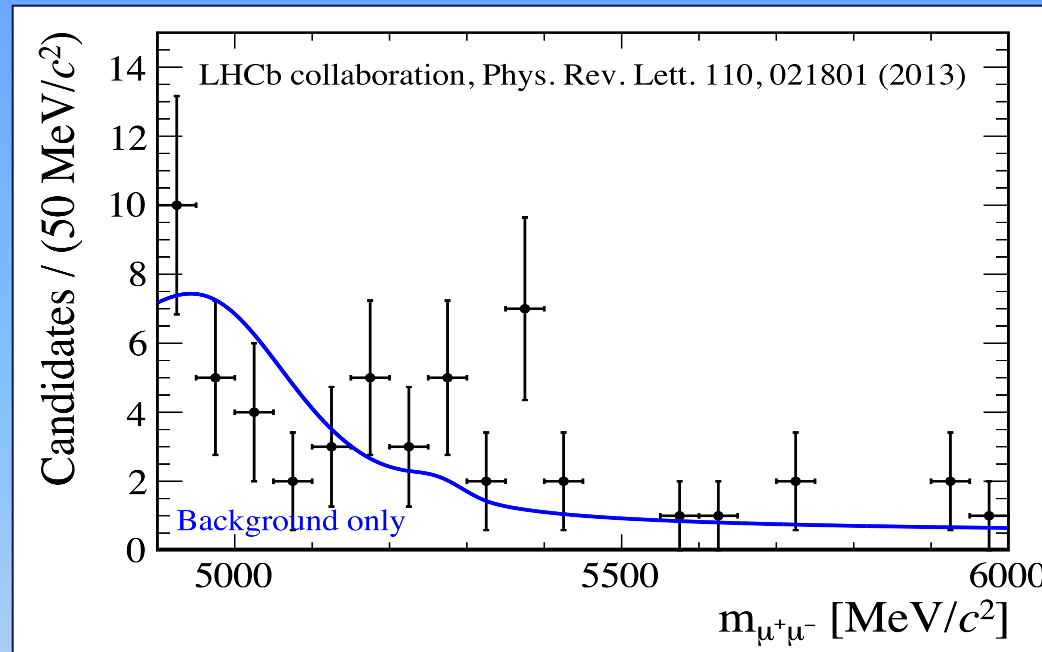
2) Find new particles

$B^0_s \to \mu\mu$



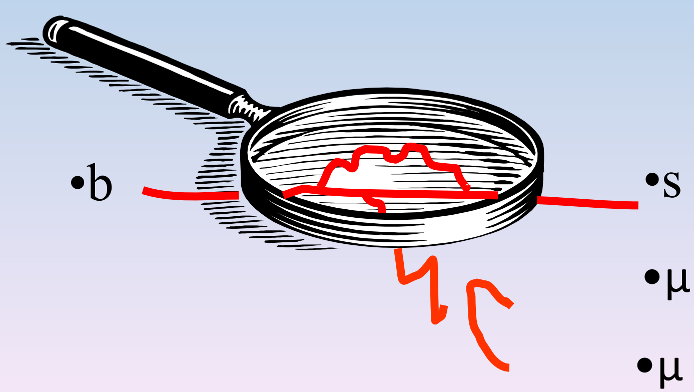


LHCb: study the *B* particle

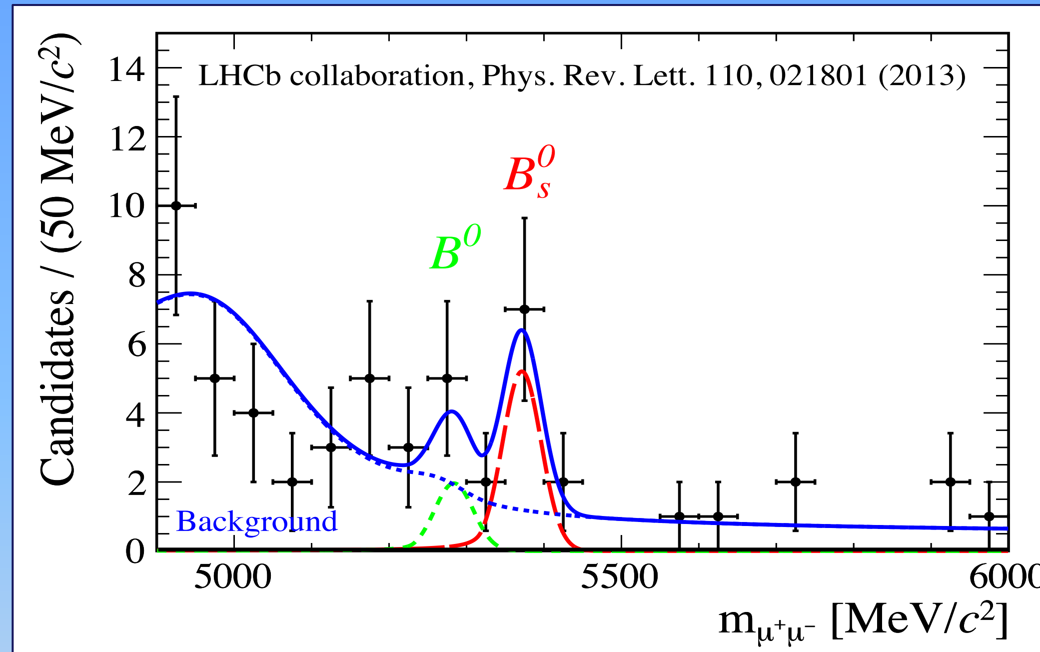


Only 3 in a billion *B* particles decay to 2 muons

Do new particles exist?

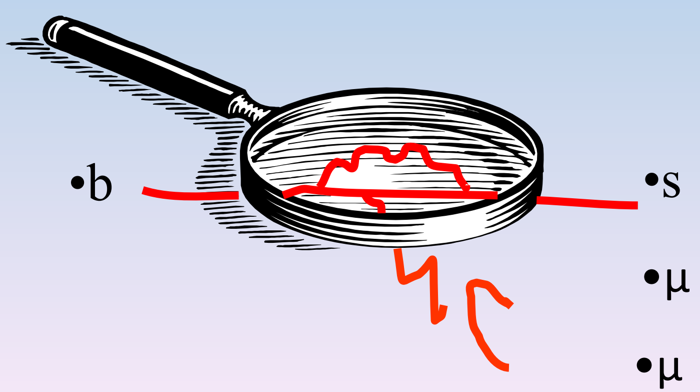


LHCb: study the *B* particle

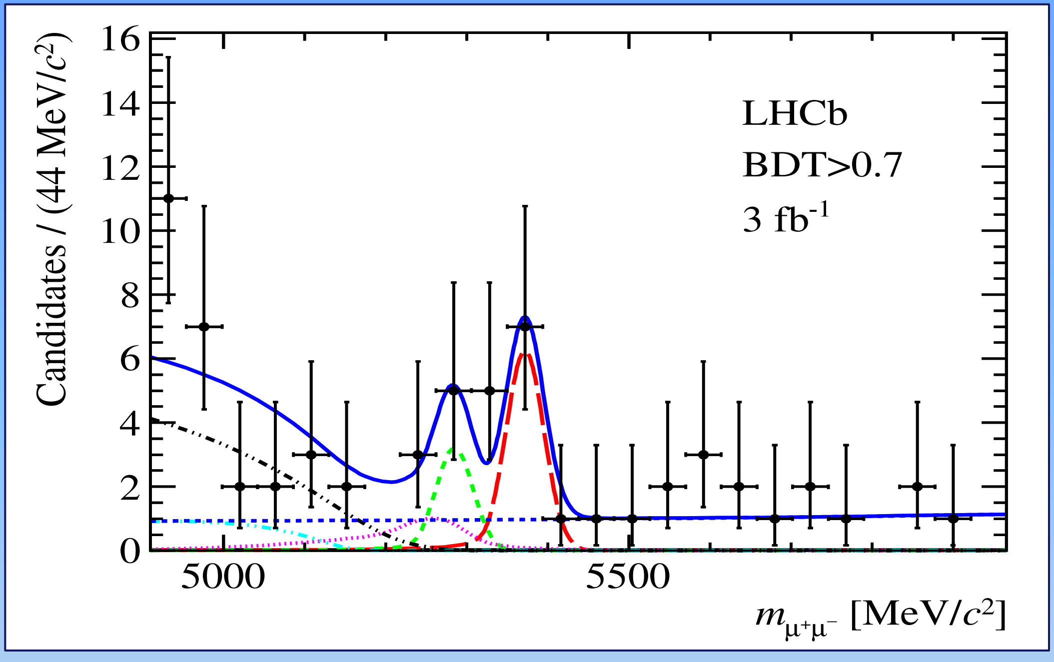


Only 3 in a billion *B* particles decay to 2 muons

Do new particles exist?

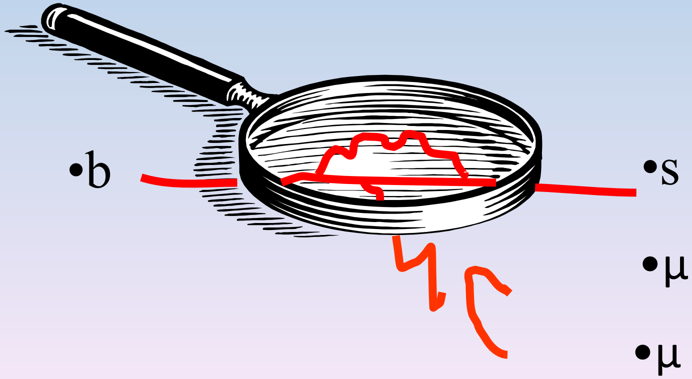


LHCb: study the *B* particle

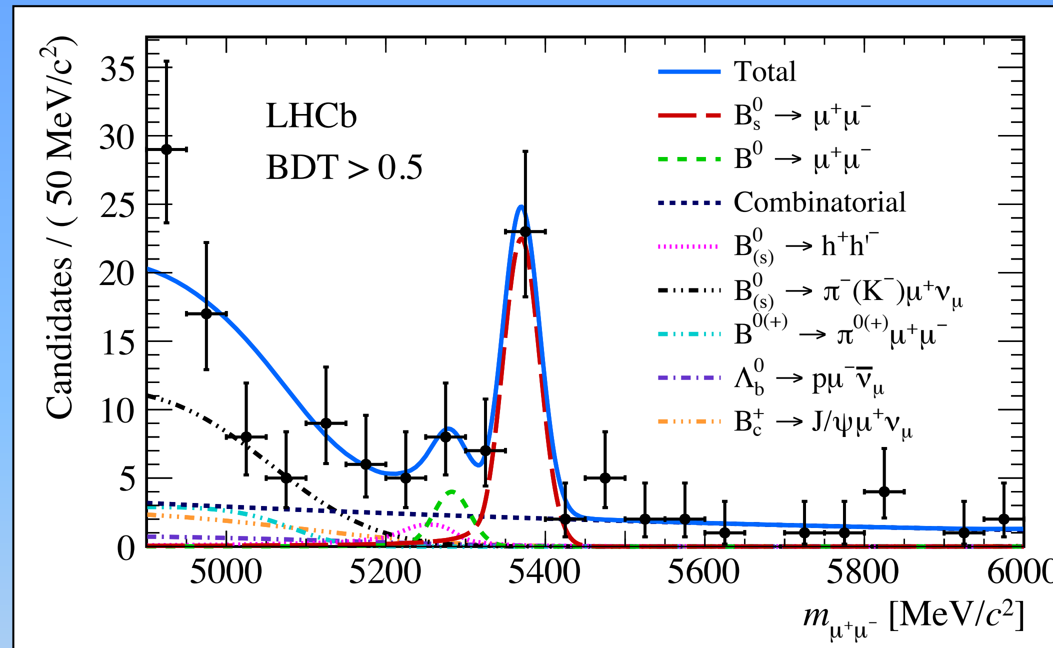


Only 3 in a billion *B* particles decay to 2 muons

Do new particles exist?

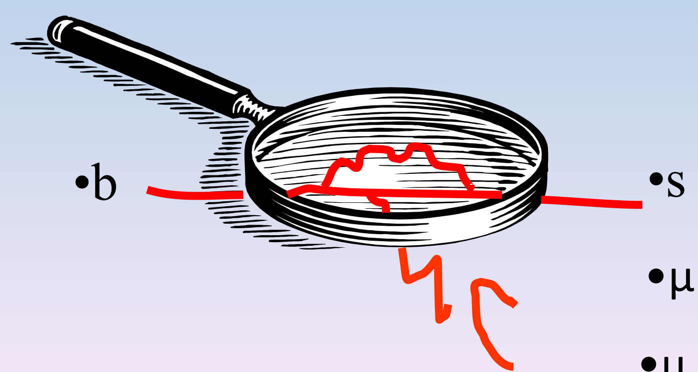


LHCb: study the *B* particle

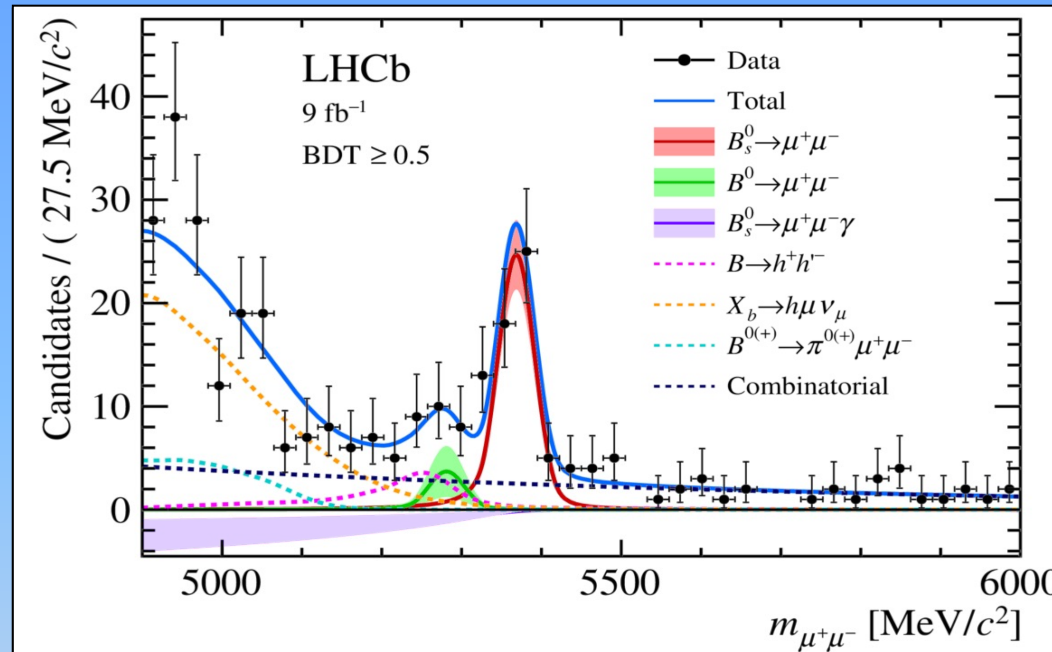


Slechts 3 op de miljard *B* deeltjes vervalt naar 2 muonen

Bestaan er nieuwe deeltjes?



LHCb: study the B particle

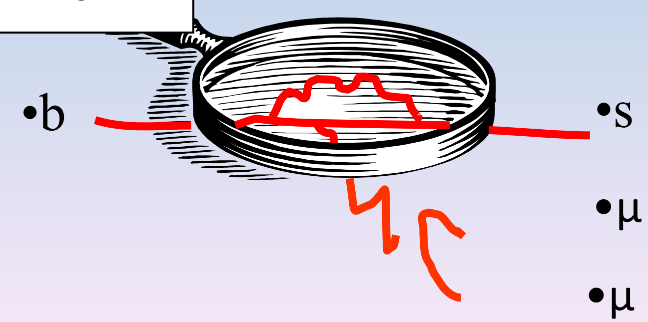


- Phys. Rev. Lett. 128, (2022) 041801

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(3.09\,^{+\,0.46\,+\,0.15}_{-\,0.43\,-\,0.11}\right) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(1.2\,^{+\,0.8}_{-\,0.7} \pm 0.1\right) \times 10^{-10}$$

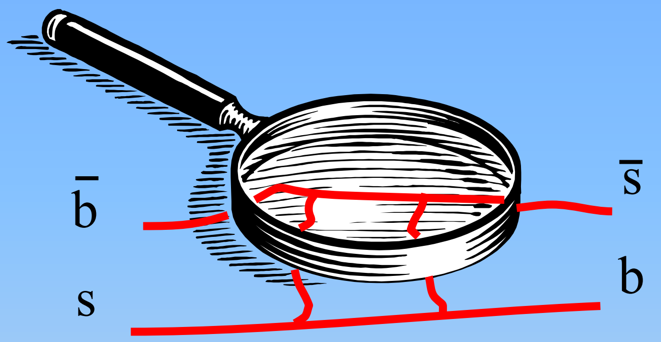
Theory :

$$B(B_s^0 \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$$
$$B(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

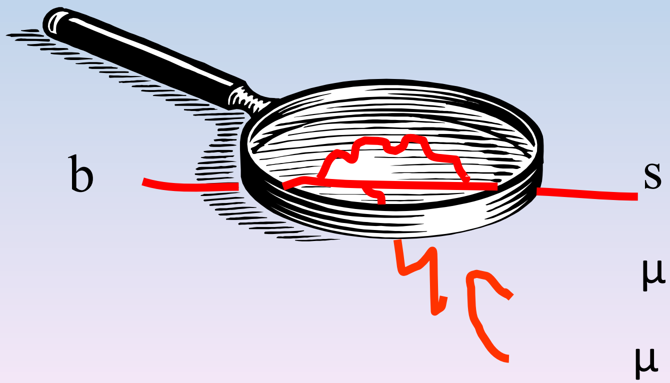


LHCb: study the *B* particle

1) Find differences between matter and anti-matter



2) Find new particles



LHCb: highlights

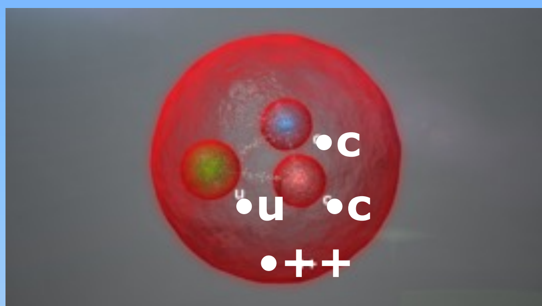
1) New ‘ordinary’ hadrons
2) New ‘exotic’ hadrons: Tetraquark and pentaquark
3) Discovery ‘CP violation’ B_s
4) Discovery ‘CP violation’ charm

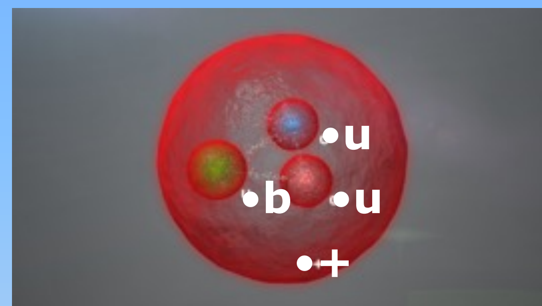
Hot topic:

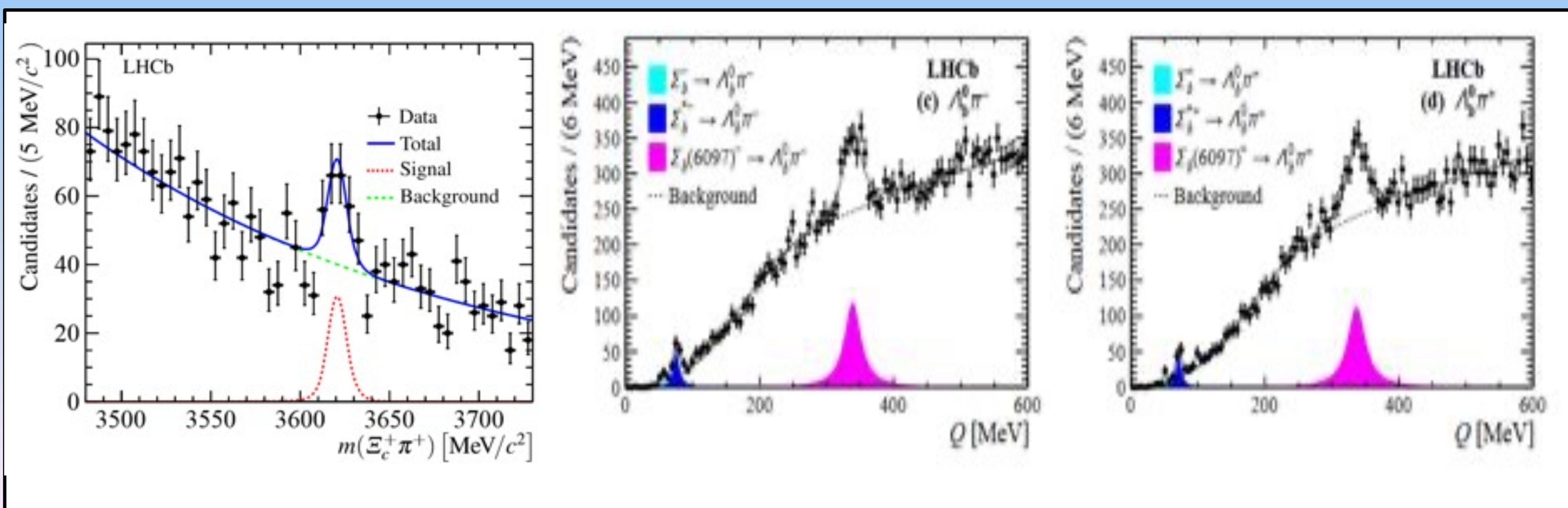
5) Difference electron, muon, tau?

LHCb: new ‘ordinary’ hadrons

(ccu): $\boldsymbol{\Xi_{cc}^{++}}$ (buu): $\boldsymbol{\Sigma_b(6097)^+}$ (bdd): $\boldsymbol{\Sigma_b(6097)^-}$



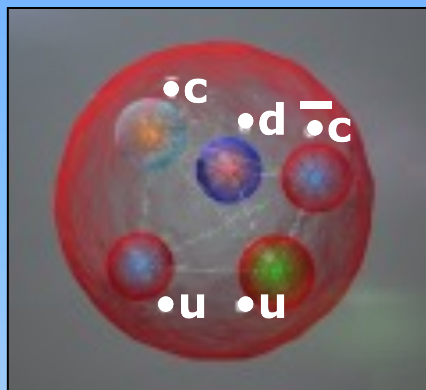


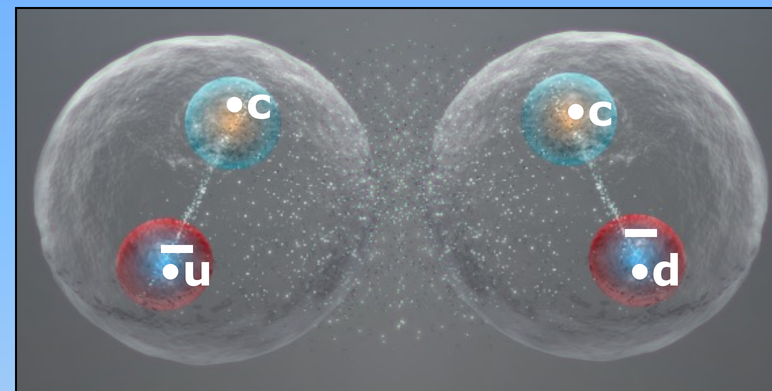


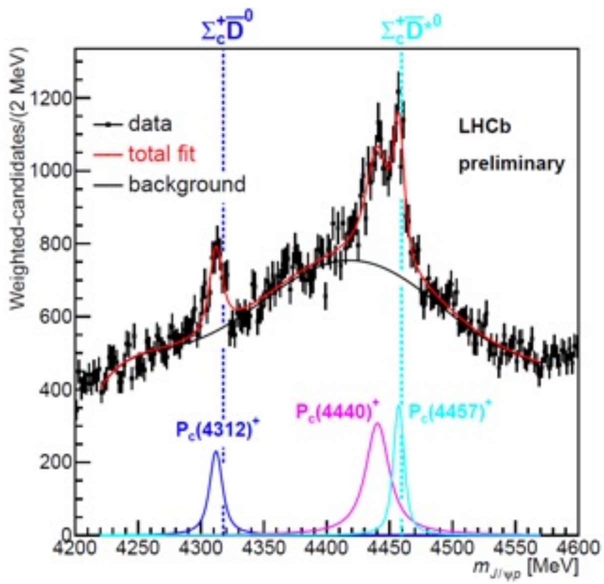
LHCb: new 'exotic' hadrons

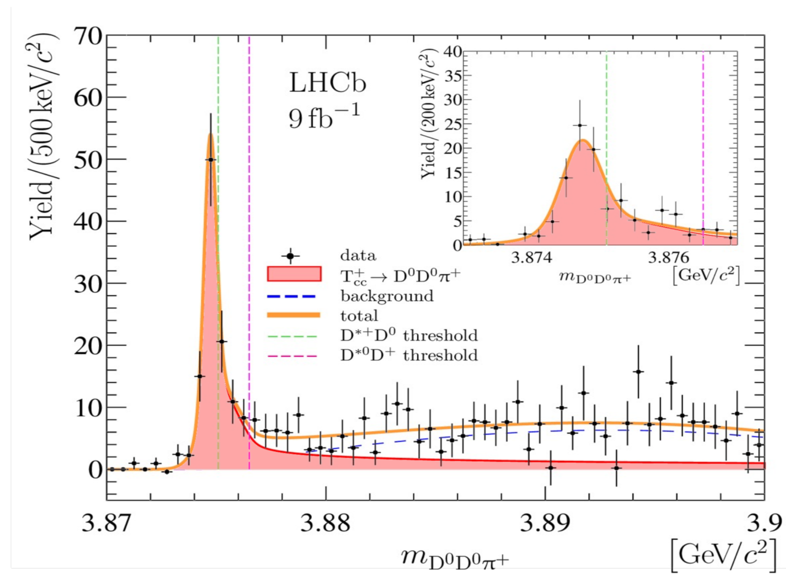
($c\bar{c}duu$): $\mathbf{P_c(4312)^+}$

($c\bar{u}\ c\bar{d}$): $\mathbf{T_{cc}{}^+(3875)}$





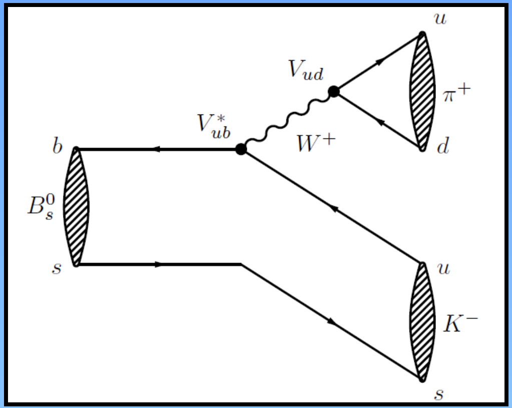


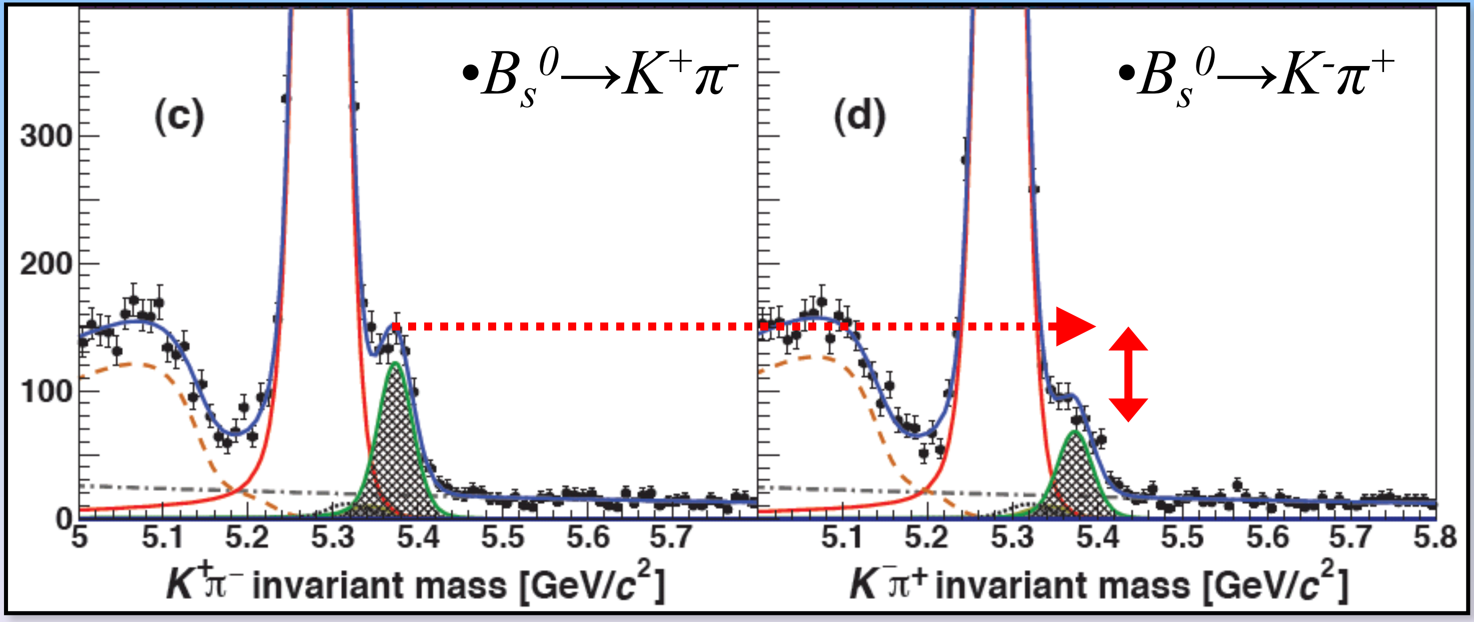


•Nature Commun. 13 (2022) 1, 3351

LHCb: antimatter difference in B_s^0

CP violation in B_s^0





LHCb: antimatter difference in charm

"CP violation"

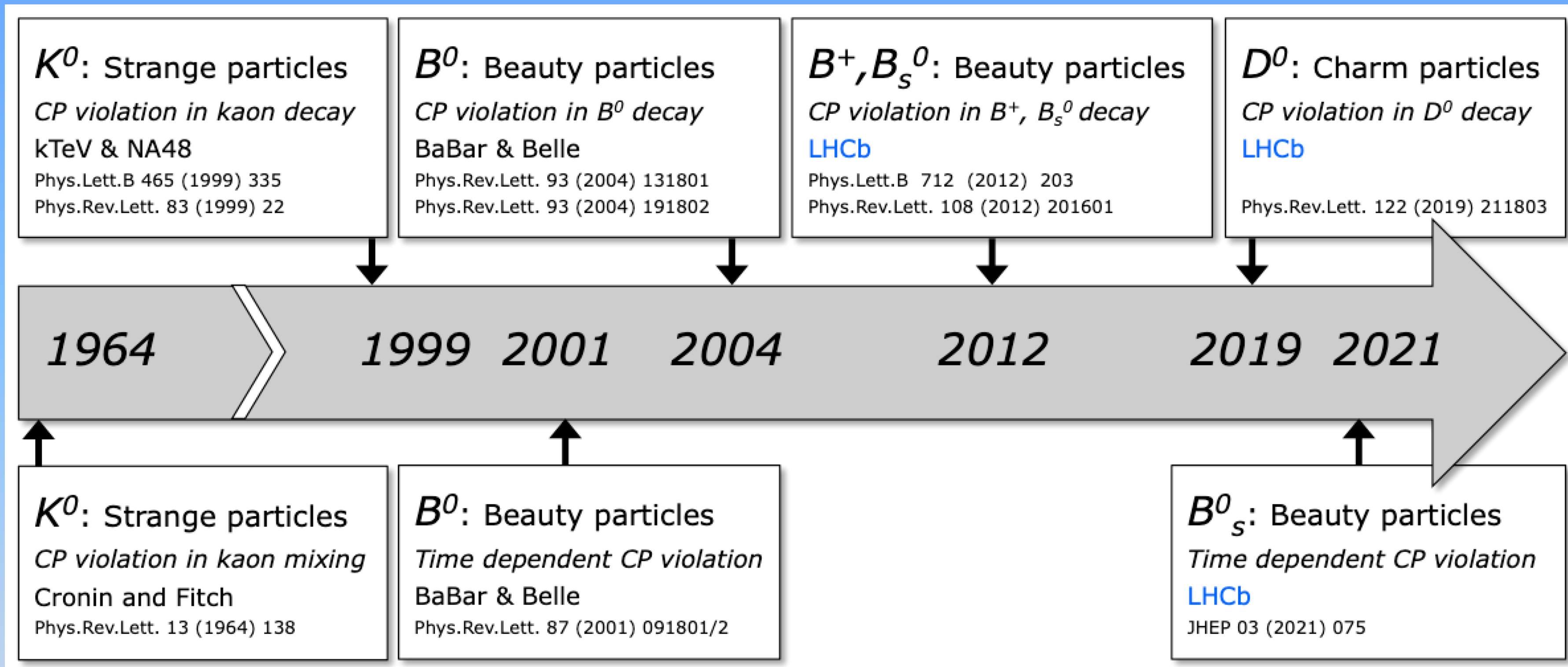
$D^0 \rightarrow K^+K^-$ same as

$\overline{D}^0 \rightarrow K^+K^-$??

at least it is different compared to
$D^0 \rightarrow \pi^+\pi^-$...:

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

LHCb: antimatter differences



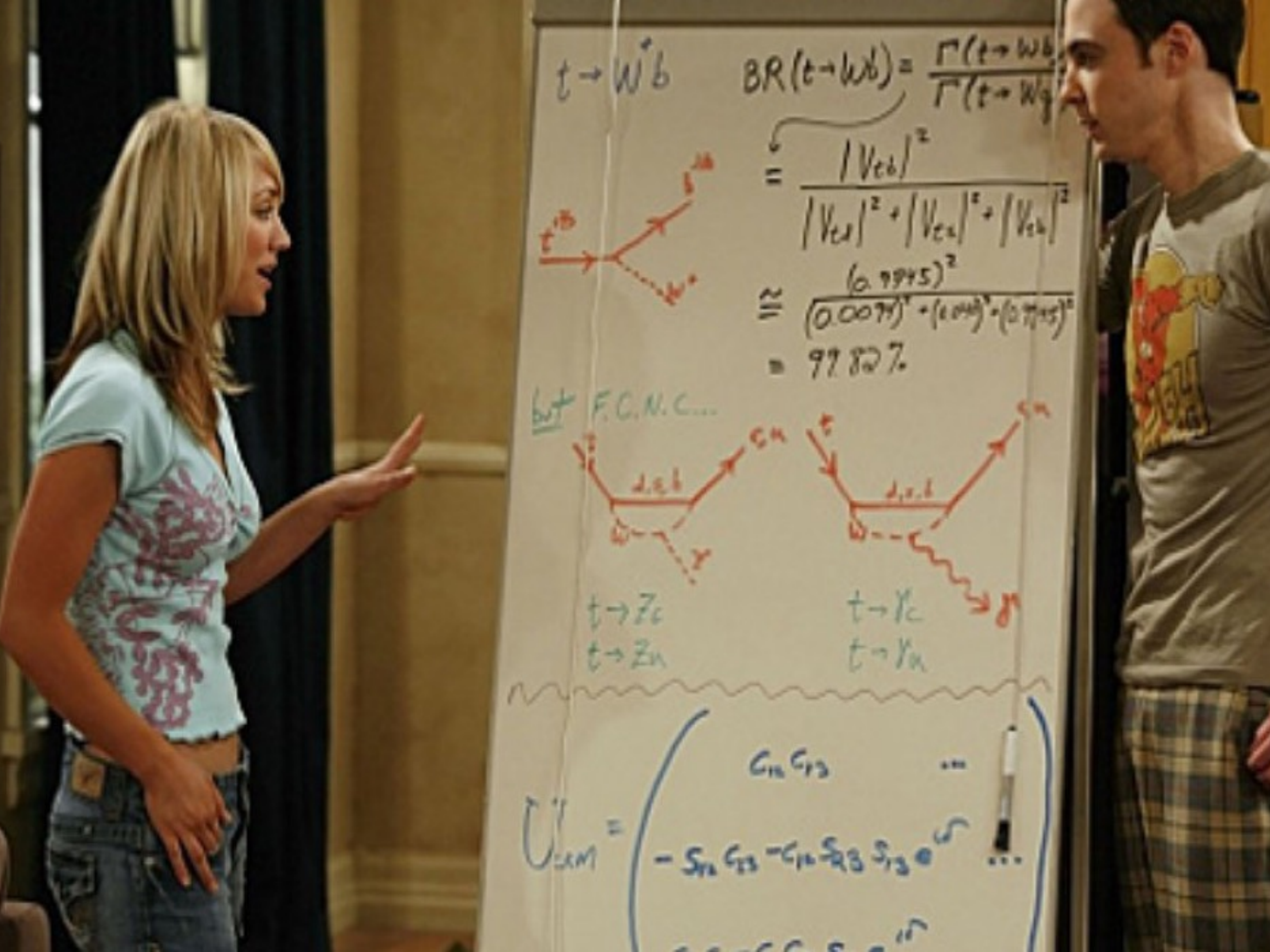
(ds)	**1964**: CP violation with K^0	(Nobelprize 1980)
(bd)	**2000**: CP violation with B^0	(Nobelprize 2008)
(bs)	**2012**: CP violation with B^0_s	(LHCb)
(cu)	**2019**: CP violation with D^0	(LHCb)

LHCb: highlights

1) New ‘ordinary’ hadrons
2) New ‘exotic’ hadrons: Tetraquark and pentaquark
3) Discovery ‘CP violation’ B_s
4) Discovery ‘CP violation’ charm

Hot topic:

5) Difference electron, muon, tau?


t → W⁺b
BR(t→Wb) =
|Vtb|²
|Vtd|² + |Vts|² + |Vtb|²
= 99.82%
but F.C.N.C...
d,s,b
d,s,b
t → Zc
t → Zu
t → γc
t → γu
U CKM =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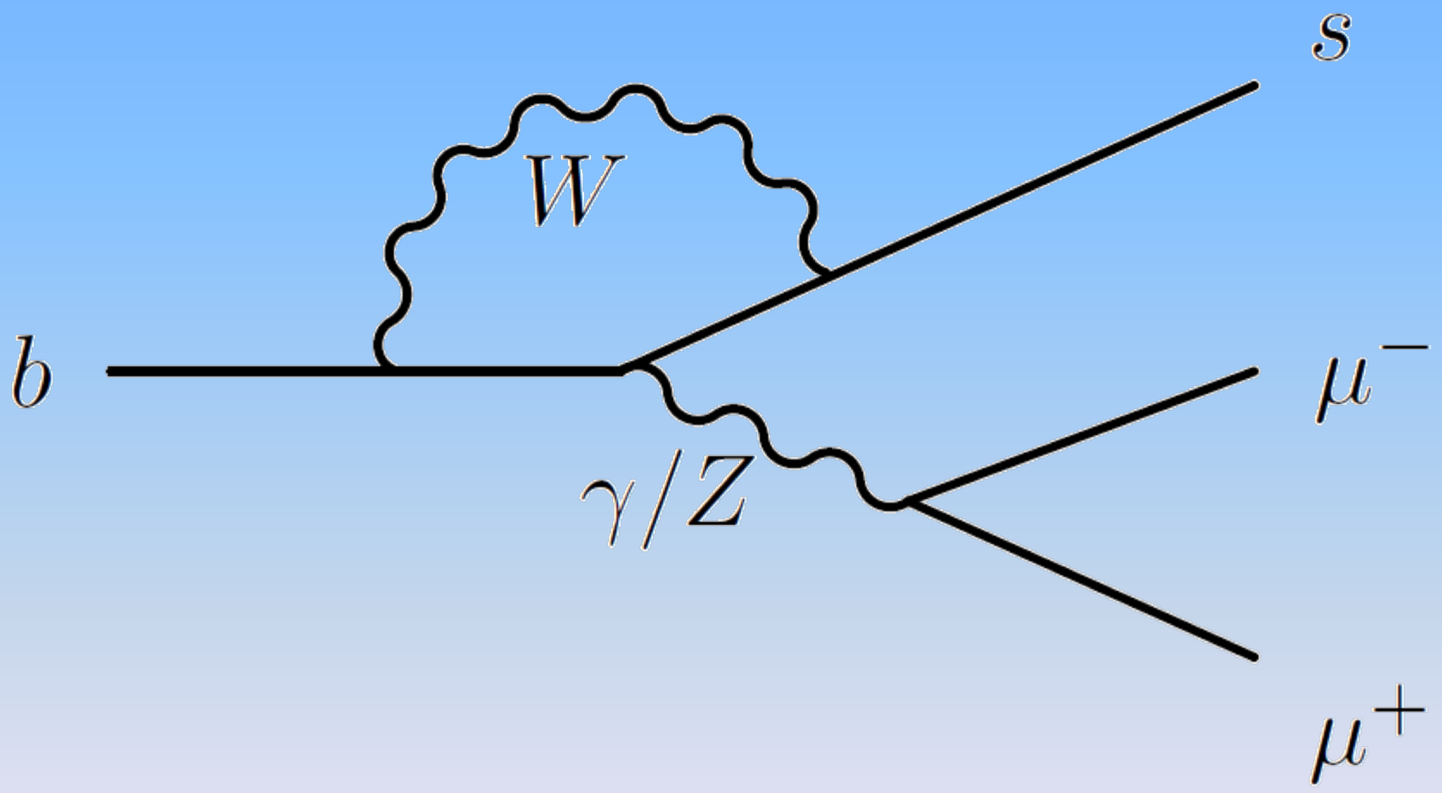
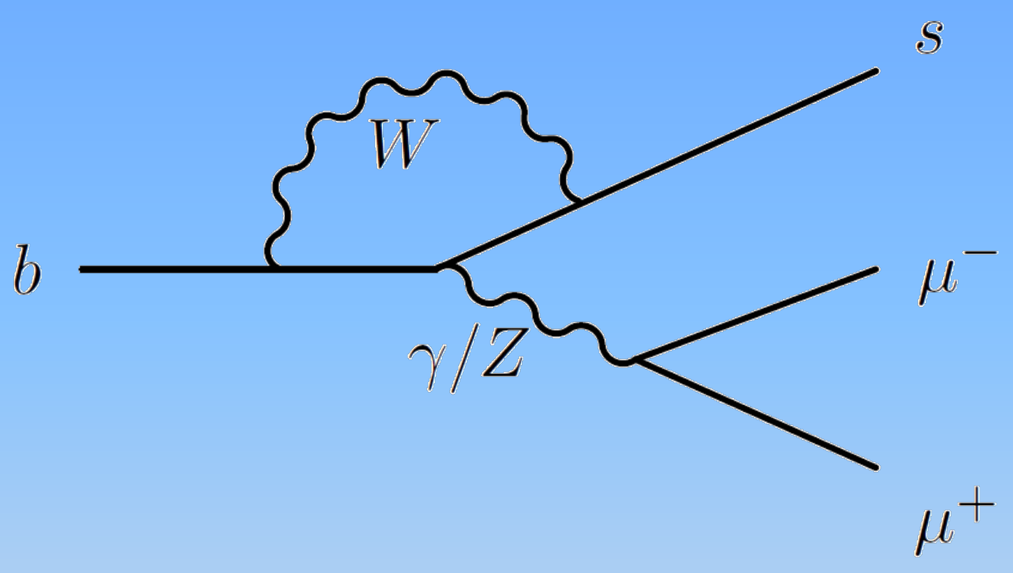
CERNCOURIER
VOLUME 55 NUMBER 9 NOVEMBER 2015
Tensions in the Standard Model

LHCb: hot topic



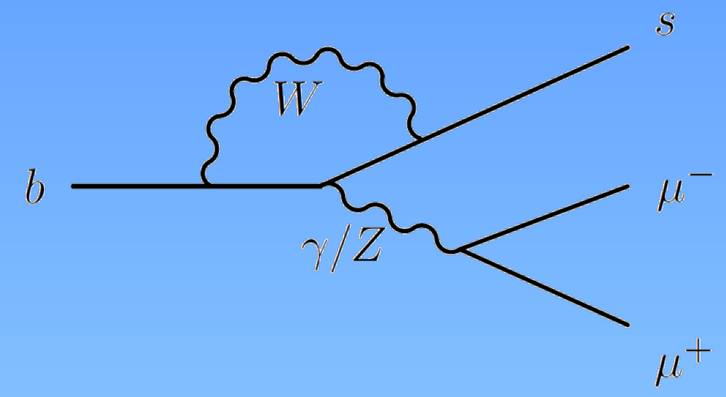
LHCb: hot topic



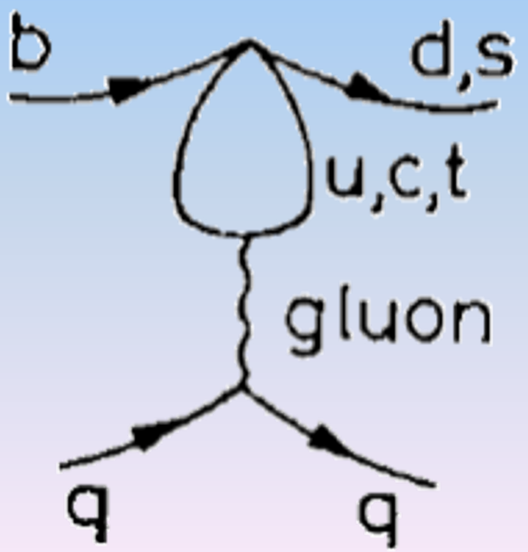
Flavour changing neutral current electroweak penguin

FCNC EWP

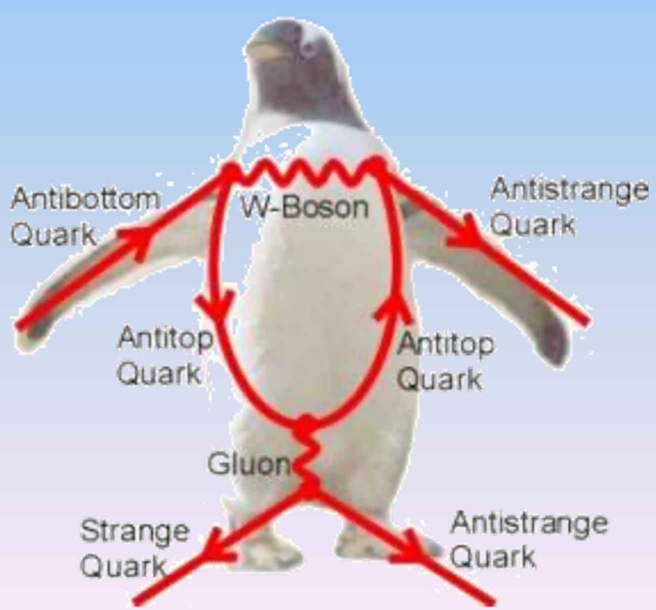
LHCb: hot topic



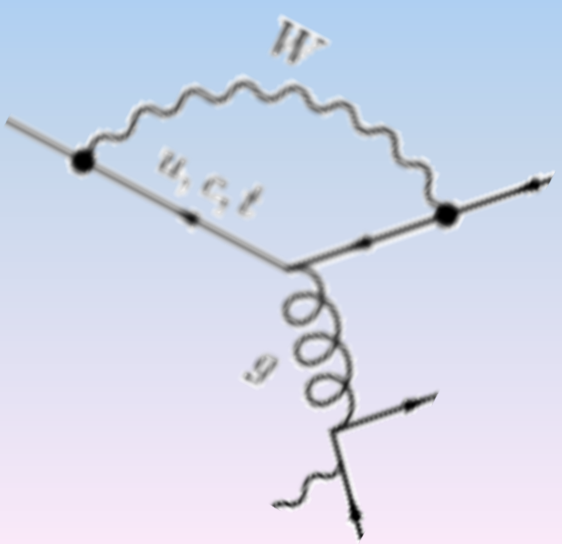
The original penguin:



A real penguin:

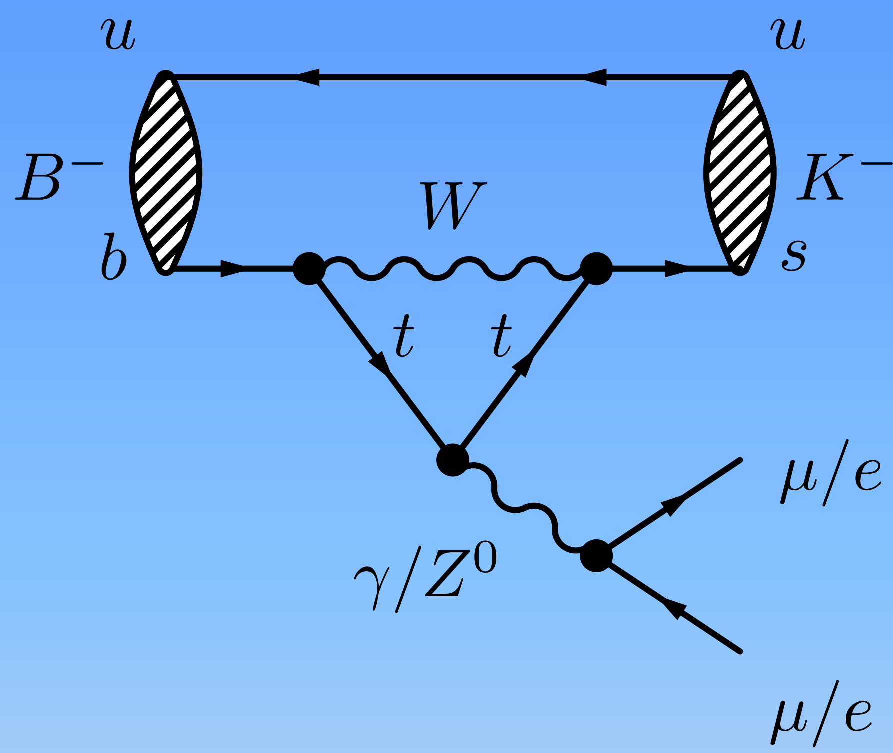


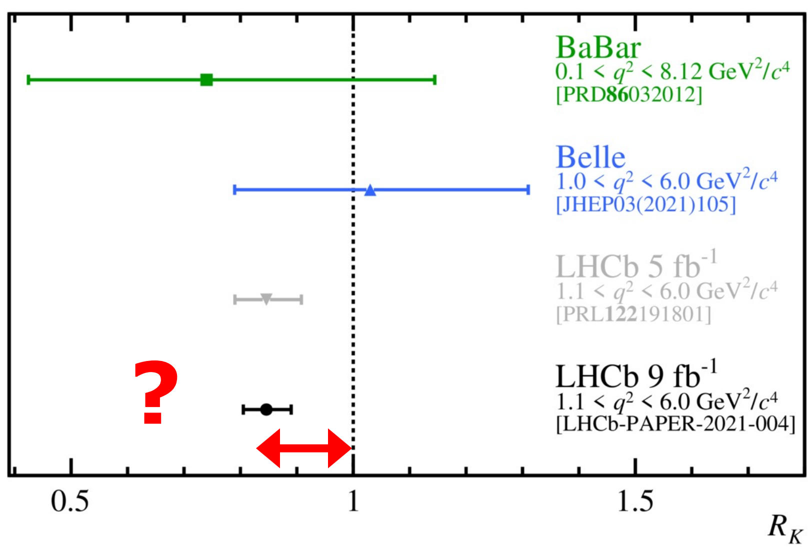
Our penguin:

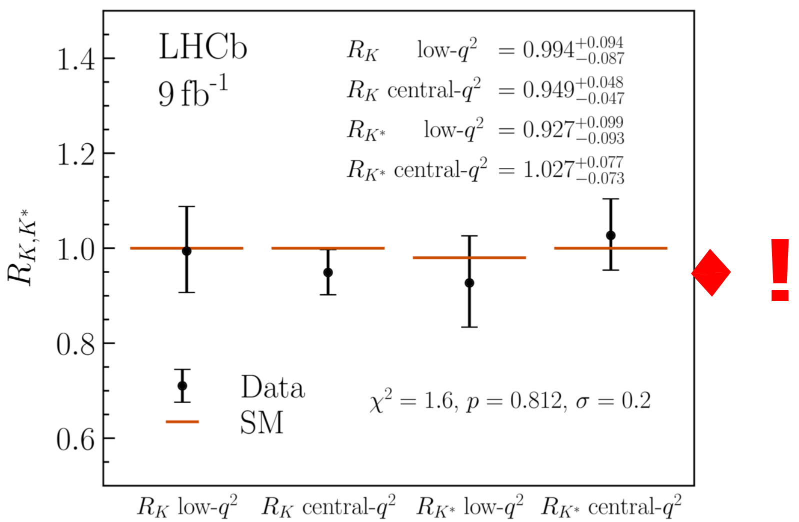


LHCb: hot topic

Electrons and muons 'behave' differently?

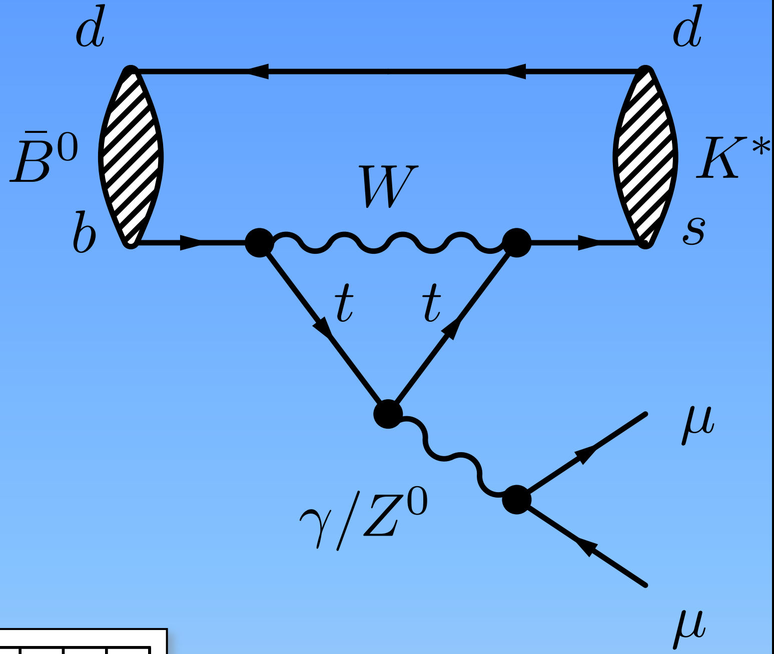


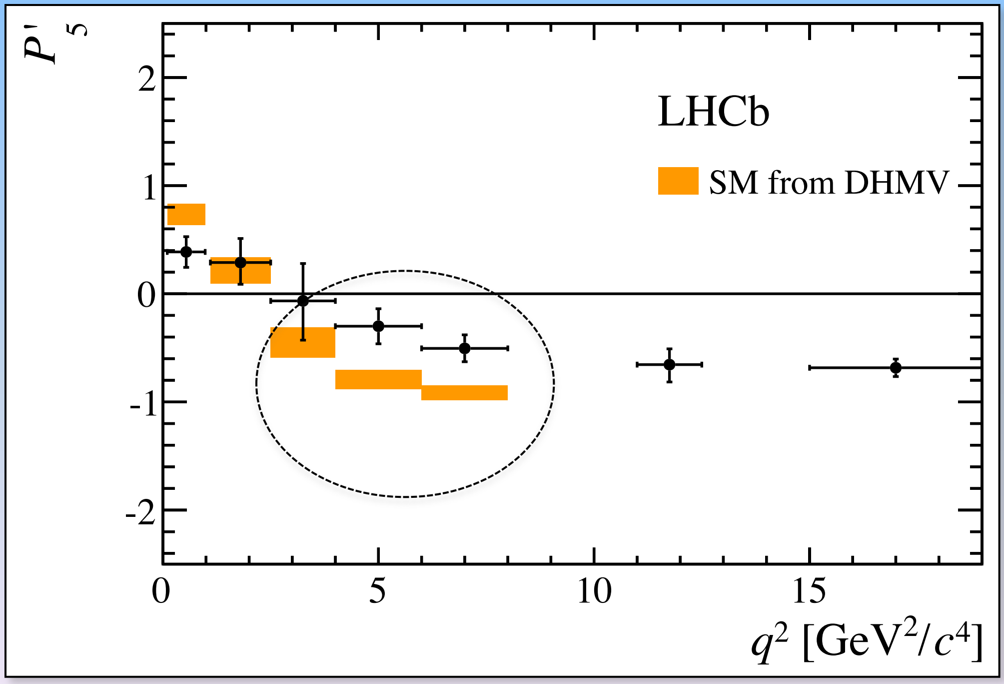




LHCb: hot topic

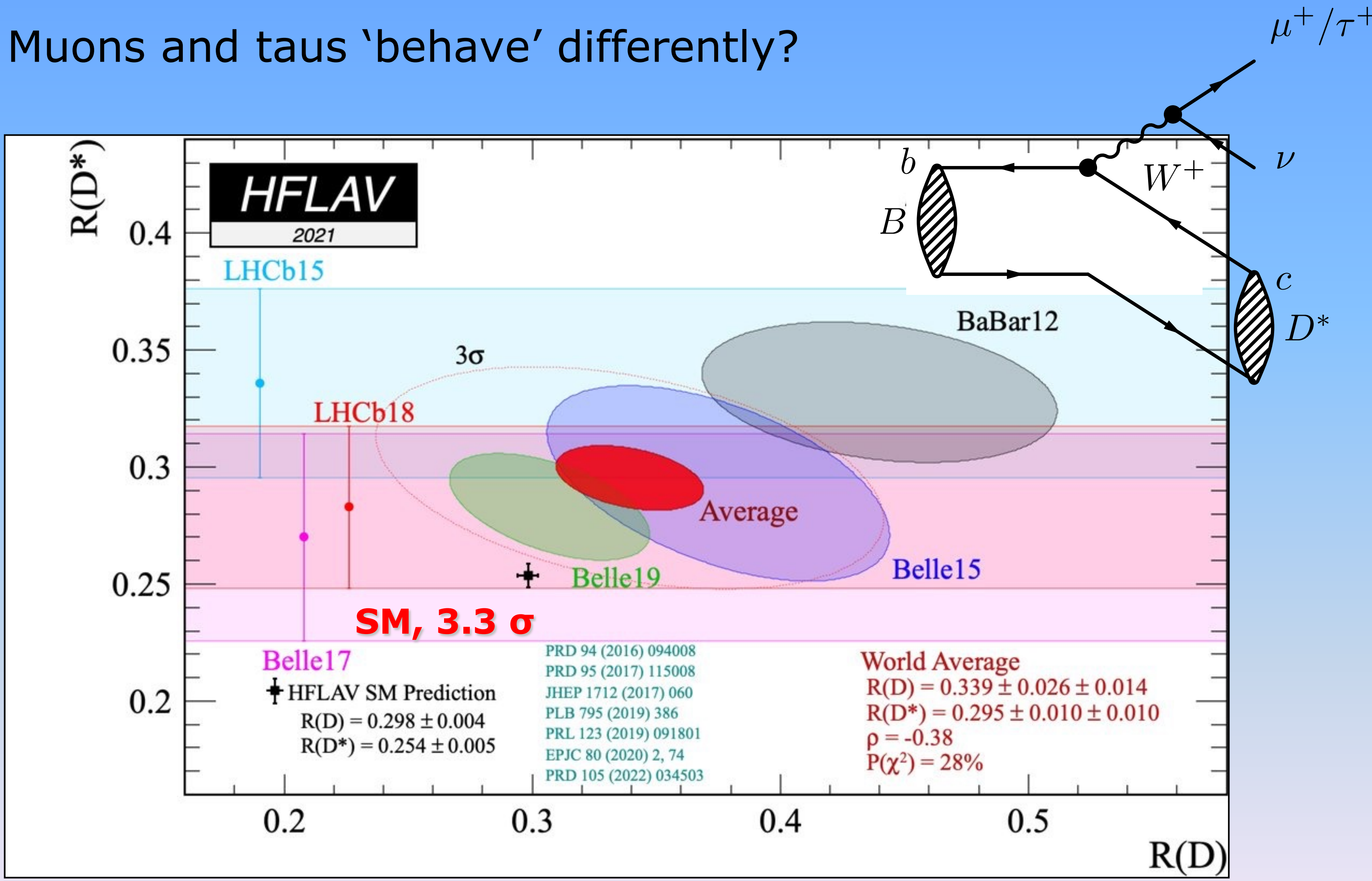
Angular distribution of muons?





LHCb: hot topic

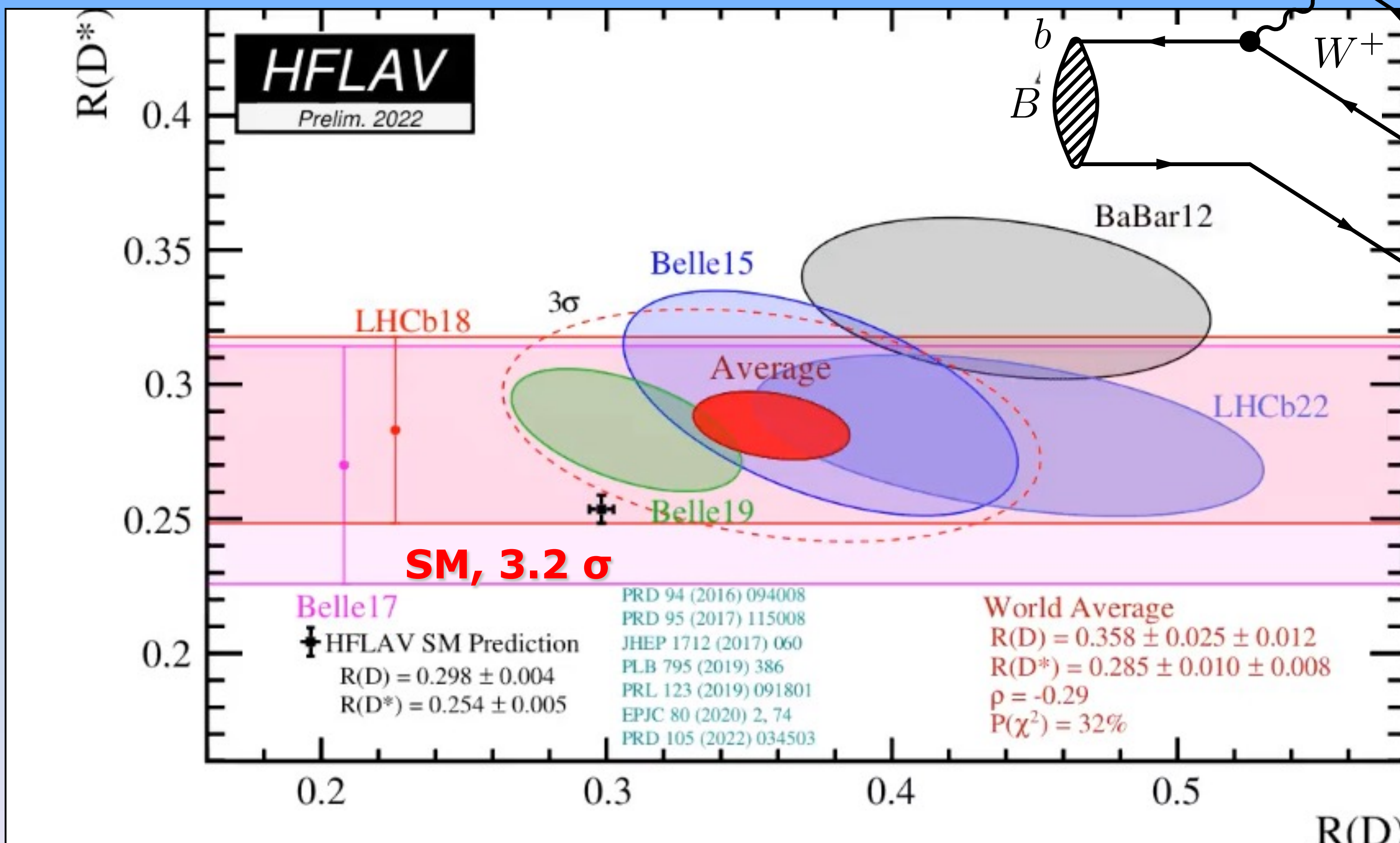
Muons and taus 'behave' differently?

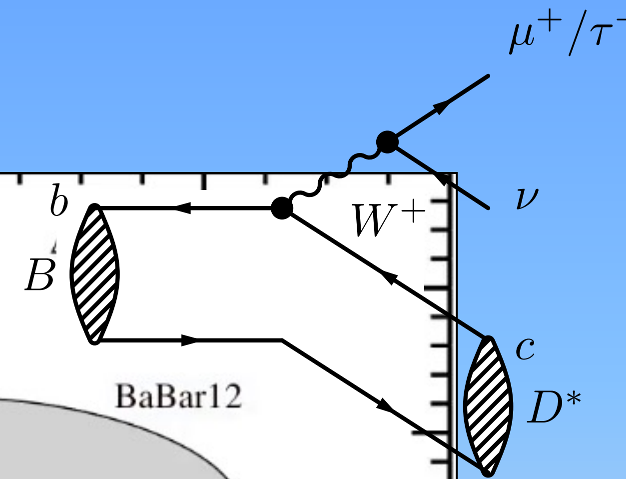


•NB: contours contain less than 68% CL…

LHCb: hot topic

Nieuw resultaat van okt 2022

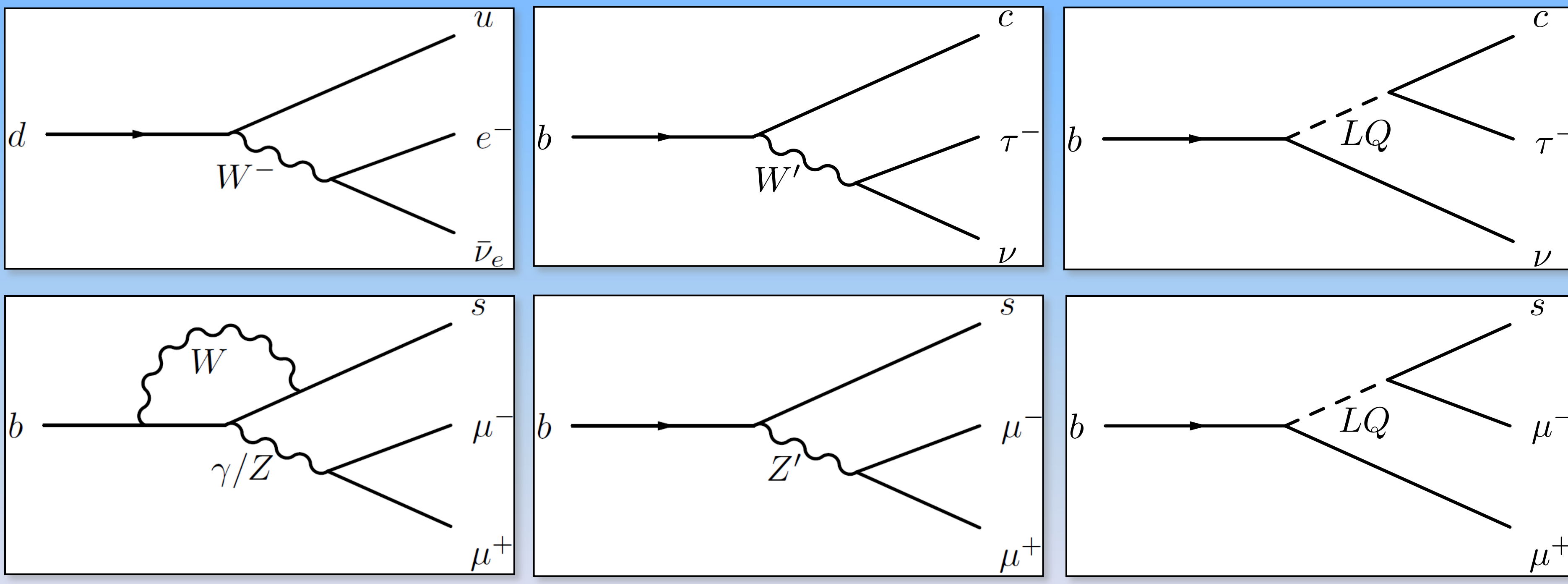




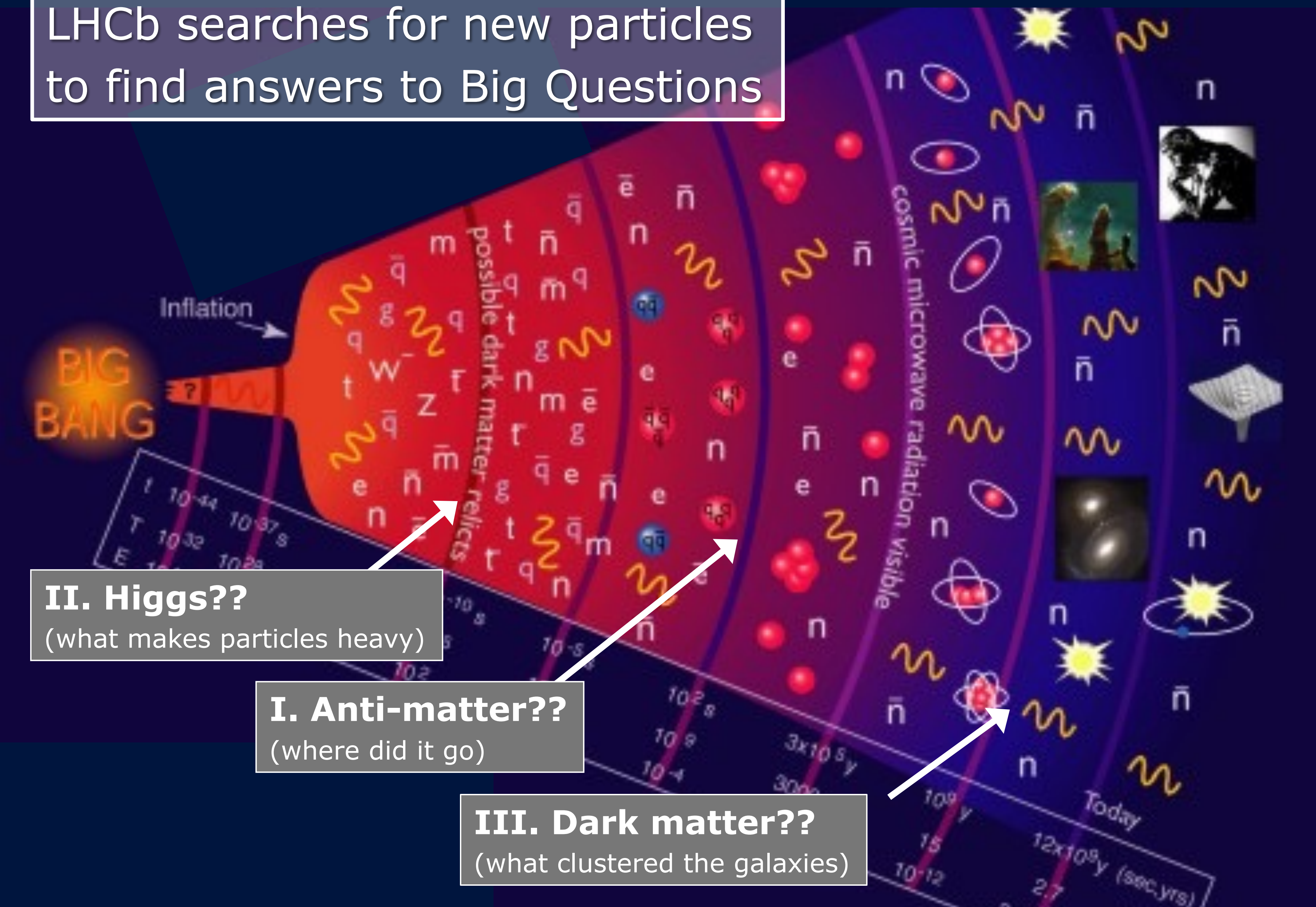
•https://hflav-eos.web.cern.ch/hflav-eos/semi/fall22/html/RDsDsstar/RDRDs.html

LHCb: what could it be?

SM | SU(2)′ | Leptoquark



LHCb searches for new particles to find answers to Big Questions



II. Higgs??
(what makes particles heavy)

I. Anti-matter??
(where did it go)

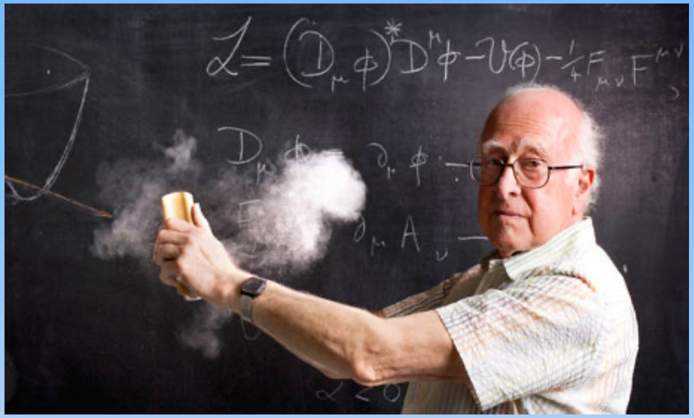
III. Dark matter??
(what clustered the galaxies)

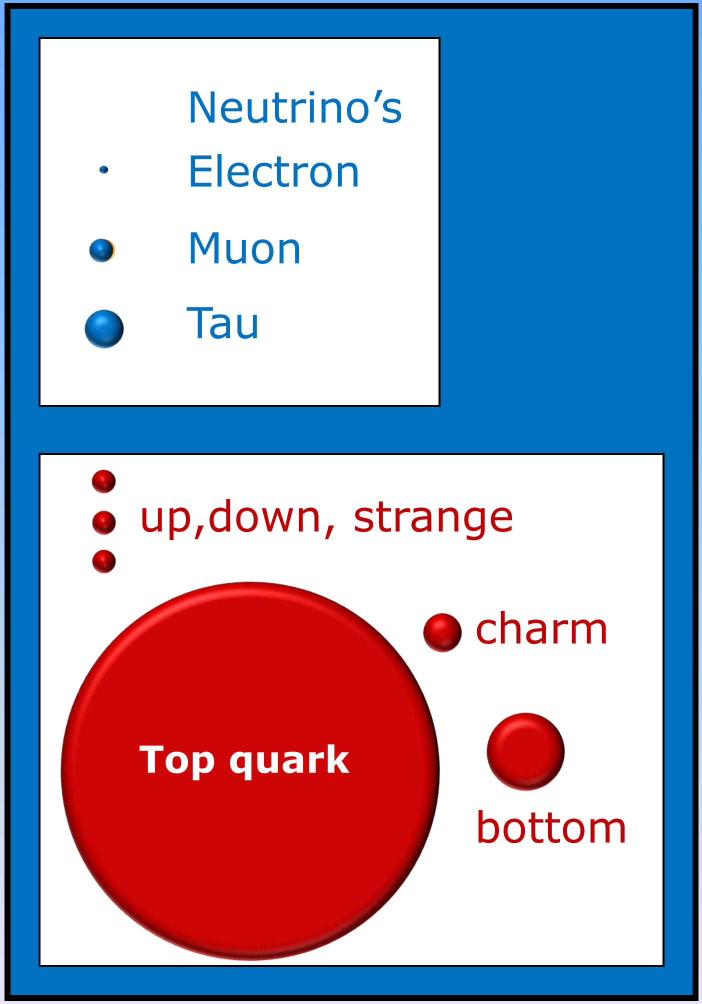
Thank you!

Higgs en LHCb

What is yet unknown? "*Higgs*"

Mass of particles





Curious prediction:

The Higgs boson:
ensures that particles have mass in the theory

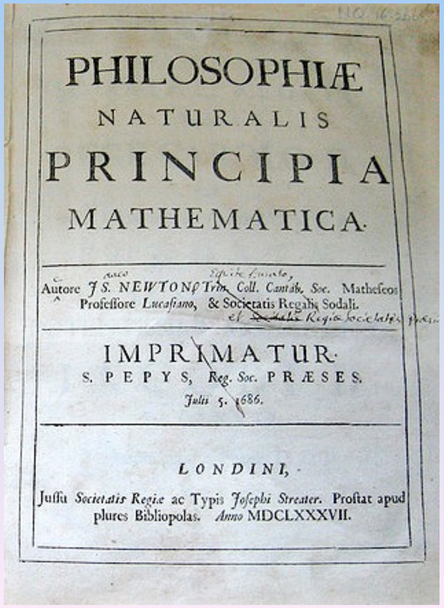
What is mass ?? Anno 1687

Mass is de ‘exchange rate’ between force and acceleration:

$$\mathbf{F = m \times a}$$

Does not describe what mass **is** ...

Newton



PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

Autore J S. NEWTONO, Trin. Coll. Cantab. Soc. Matheseos Professore Lucasiano, & Societatis Regalis Sodali.

IMPRIMATUR.
S. PEPYS, Reg. Soc. PRÆSES.
Julii 5. 1686.

LONDINI,
Jussu Societatis Regiæ ac Typis Josephi Streater. Prostat apud plures Bibliopolas. Anno MDCLXXXVII.

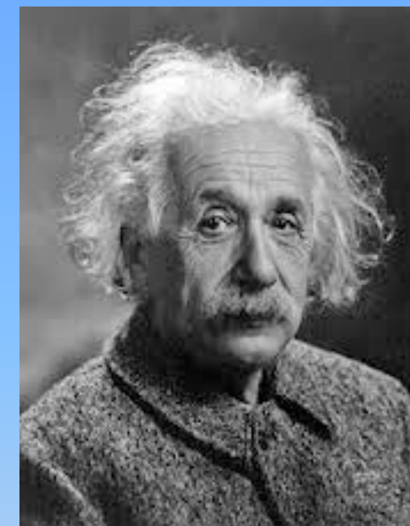
What is mass ?? Anno 1905

Mass is energy

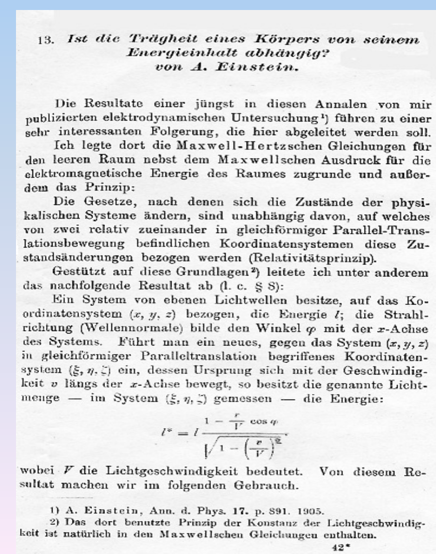
$$E = m \times c^2$$

Describes what mass ***is*** !

But not where it comes from …



Einstein



13. *Ist die Trägheit eines Körpers von seinem Energieinhalt abhängig?*
von A. Einstein.

Die Resultate einer jüngst in diesen Annalen von mir publizierten elektrodynamischen Untersuchung[1]) führen zu einer sehr interessanten Folgerung, die hier abgeleitet werden soll.

Ich legte dort die Maxwell-Hertzschen Gleichungen für den leeren Raum nebst dem Maxwellschen Ausdruck für die elektromagnetische Energie des Raumes zugrunde und außerdem das Prinzip:

Die Gesetze, nach denen sich die Zustände der physikalischen Systeme ändern, sind unabhängig davon, auf welches von zwei relativ zueinander in gleichförmiger Parallel-Translationsbewegung befindlichen Koordinatensystemen diese Zustandsänderungen bezogen werden (Relativitätsprinzip).

Gestützt auf diese Grundlagen[2]) leitete ich unter anderem das nachfolgende Resultat ab (l. c. § 8):

Ein System von ebenen Lichtwellen besitze, auf das Koordinatensystem (x, y, z) bezogen, die Energie l; die Strahlrichtung (Wellennormale) bilde den Winkel φ mit der x-Achse des Systems. Führt man ein neues, gegen das System (x, y, z) in gleichförmiger Paralleltranslation begriffenes Koordinatensystem (ξ, η, ζ) ein, dessen Ursprung sich mit der Geschwindigkeit v längs der x-Achse bewegt, so besitzt die genannte Lichtmenge — im System (ξ, η, ζ) gemessen — die Energie:

$$l^* = l \frac{1 - \frac{v}{V} \cos \varphi}{\sqrt{1 - \left(\frac{v}{V}\right)^2}},$$

wobei V die Lichtgeschwindigkeit bedeutet. Von diesem Resultat machen wir im folgenden Gebrauch.

1) A. Einstein, Ann. d. Phys. 17. p. 891. 1905.
2) Das dort benutzte Prinzip der Konstanz der Lichtgeschwindigkeit ist natürlich in den Maxwellschen Gleichungen enthalten.

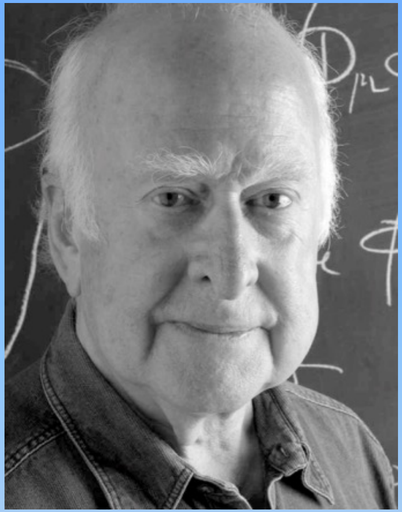
42*

What is mass ?? Anno 1964

Mass of elementary particles is due to

"friction" of ubiquitous 'Higgs field'

m: ψψH



Higgs

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS

Received 27 July 1964

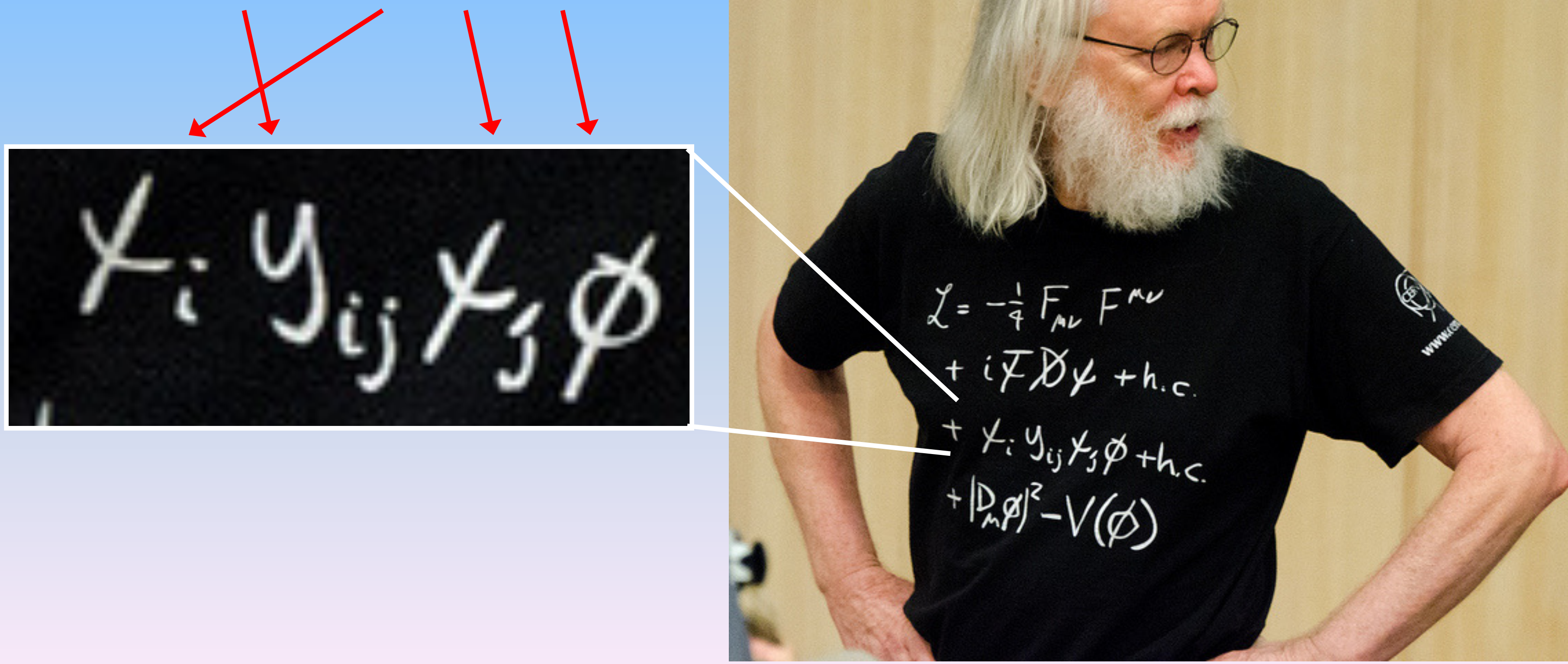
Huh?

What is mass ?? Anno 1964

Mass of elementary particles is due to

"friction" of ubiquitous 'Higgs field'

$$\mathbf{m: \psi\psi H}$$



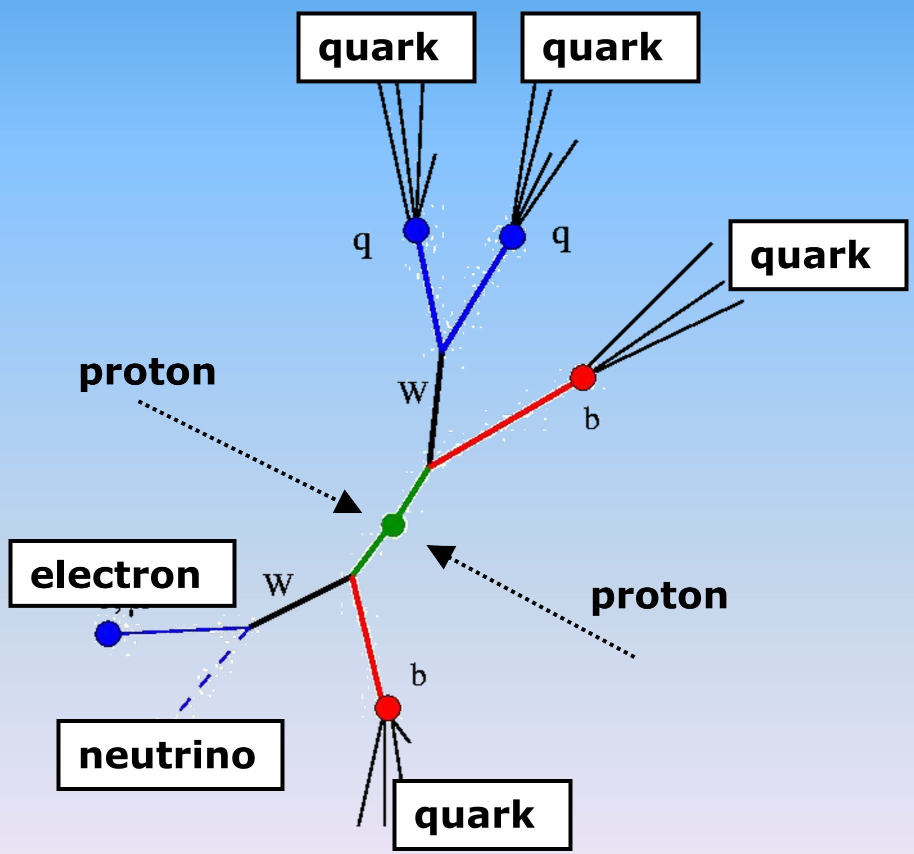
Modelling interactions

Standard Model Lagrangian

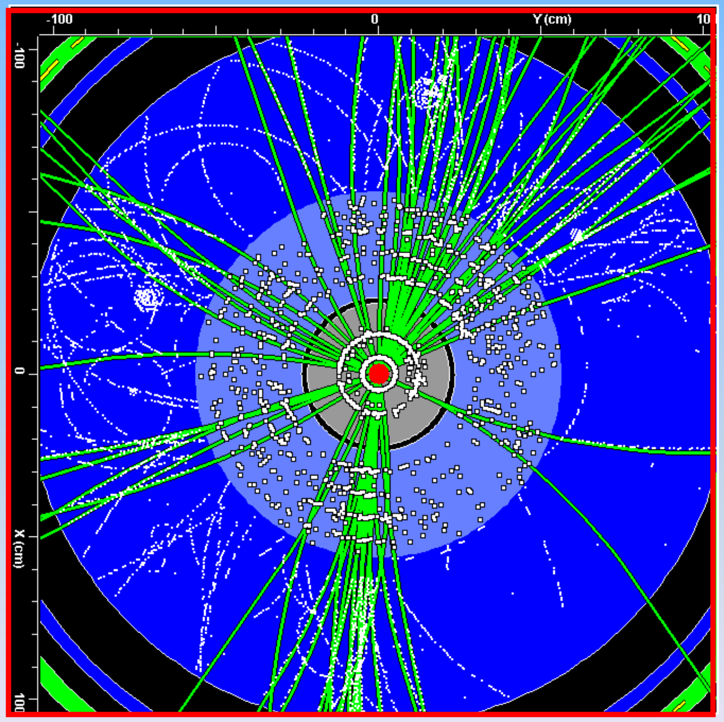
$$-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \tfrac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu +$$
$$\bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu -$$
$$\tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \tfrac{1}{2}m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \tfrac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 -$$
$$\tfrac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu +$$
$$\tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu -$$
$$A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 +$$
$$H\phi^0\phi^0 + 2H\phi^+\phi^-] - \tfrac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- +$$
$$2(\phi^0)^2H^2] - gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ -$$
$$\phi^+\partial_\mu\phi^0)] + \tfrac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)] + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 -$$
$$\phi^0\partial_\mu H) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- -$$
$$\phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] -$$
$$\tfrac{1}{4}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2-1)^2\phi^+\phi^-] - \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) -$$
$$\tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- -$$
$$W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda -$$
$$\bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) -$$
$$\tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \tfrac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 -$$
$$1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(1 +$$
$$\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}\tfrac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1 -$$
$$\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \tfrac{g}{2}\tfrac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1 -$$
$$\gamma^5)d^\kappa_j) + m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1 -$$
$$\gamma^5)u^\kappa_j] - \tfrac{g}{2}\tfrac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2}\tfrac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) +$$
$$\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- -$$
$$\partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) +$$
$$igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ -$$
$$\partial_\mu\bar{X}^- X^-) - \tfrac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2}\bar{X}^0 X^0 H] + \tfrac{1-2c_w^2}{2c_w}igM[\bar{X}^+ X^0\phi^+ -$$
$$\bar{X}^- X^0\phi^-] + \tfrac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + igMs_w[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] +$$
$$\tfrac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]$$

Music (J.S. Bach)

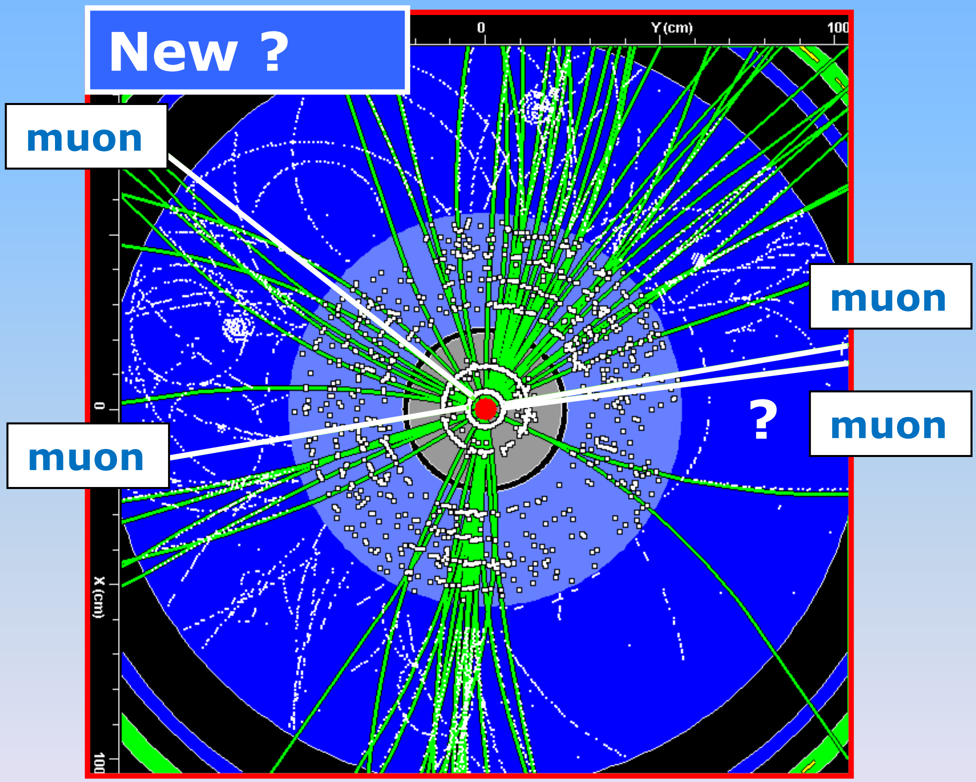
How do collissions look like?

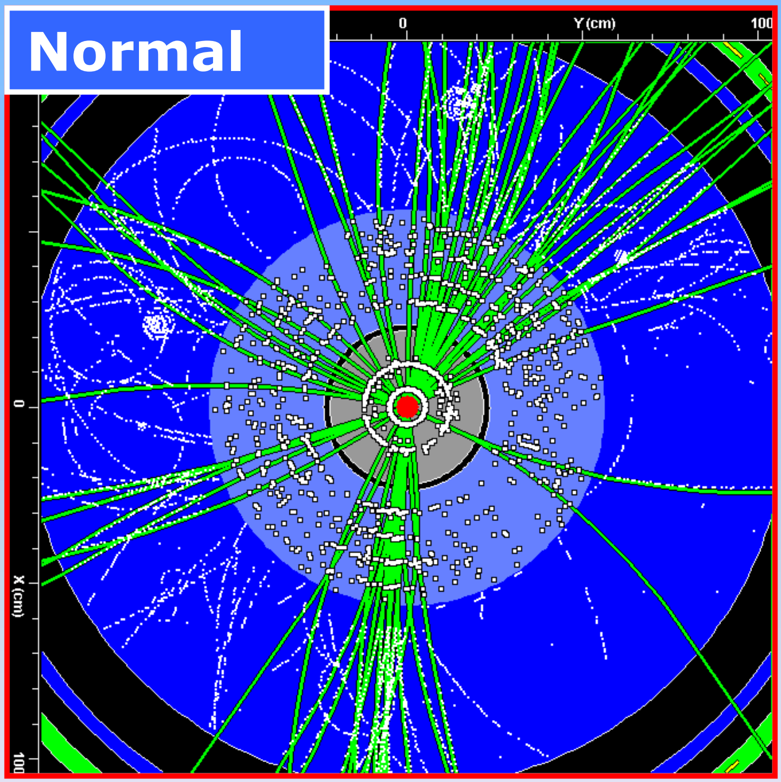


Simulation top quark production



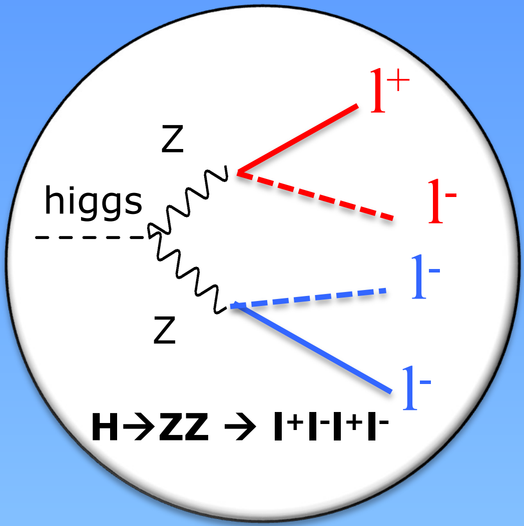
How are discoveries made?





Higgs → ZZ → 4 leptons

small number of beautiful events



120.000 Higgs bosons

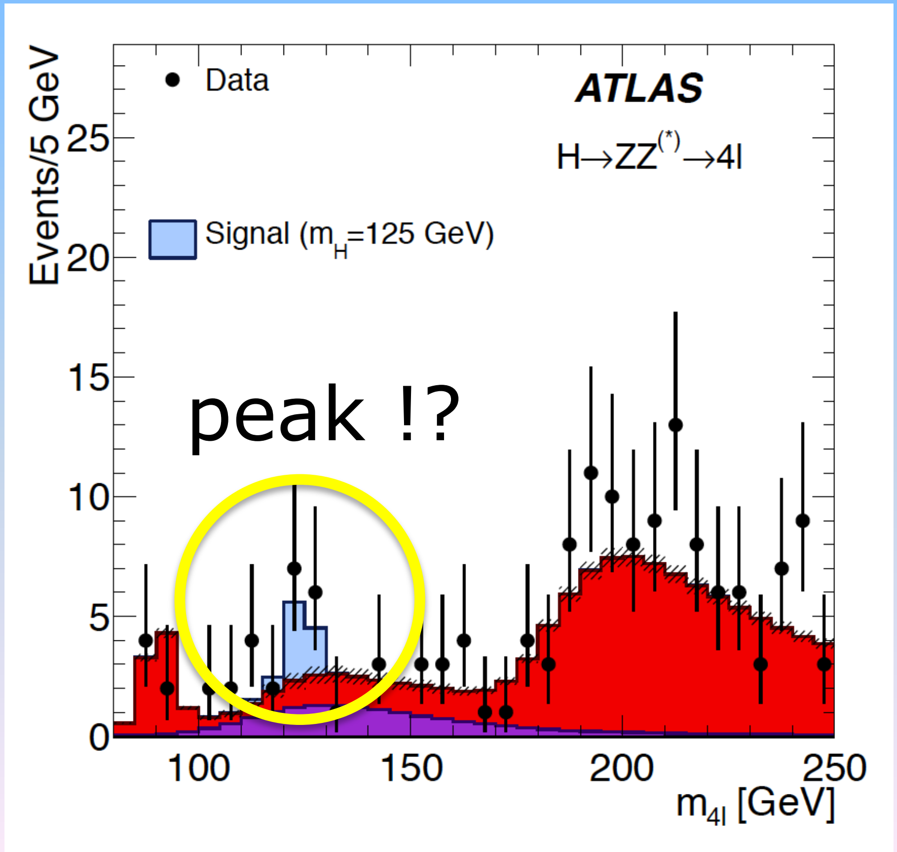
⇩

- Only 1 in 1000 Higgs bosons decays to 4 leptons
- 50% chance that ATLAS detector finds them

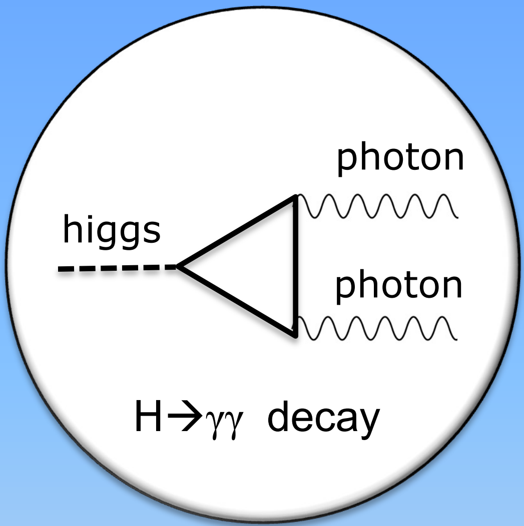
⇩

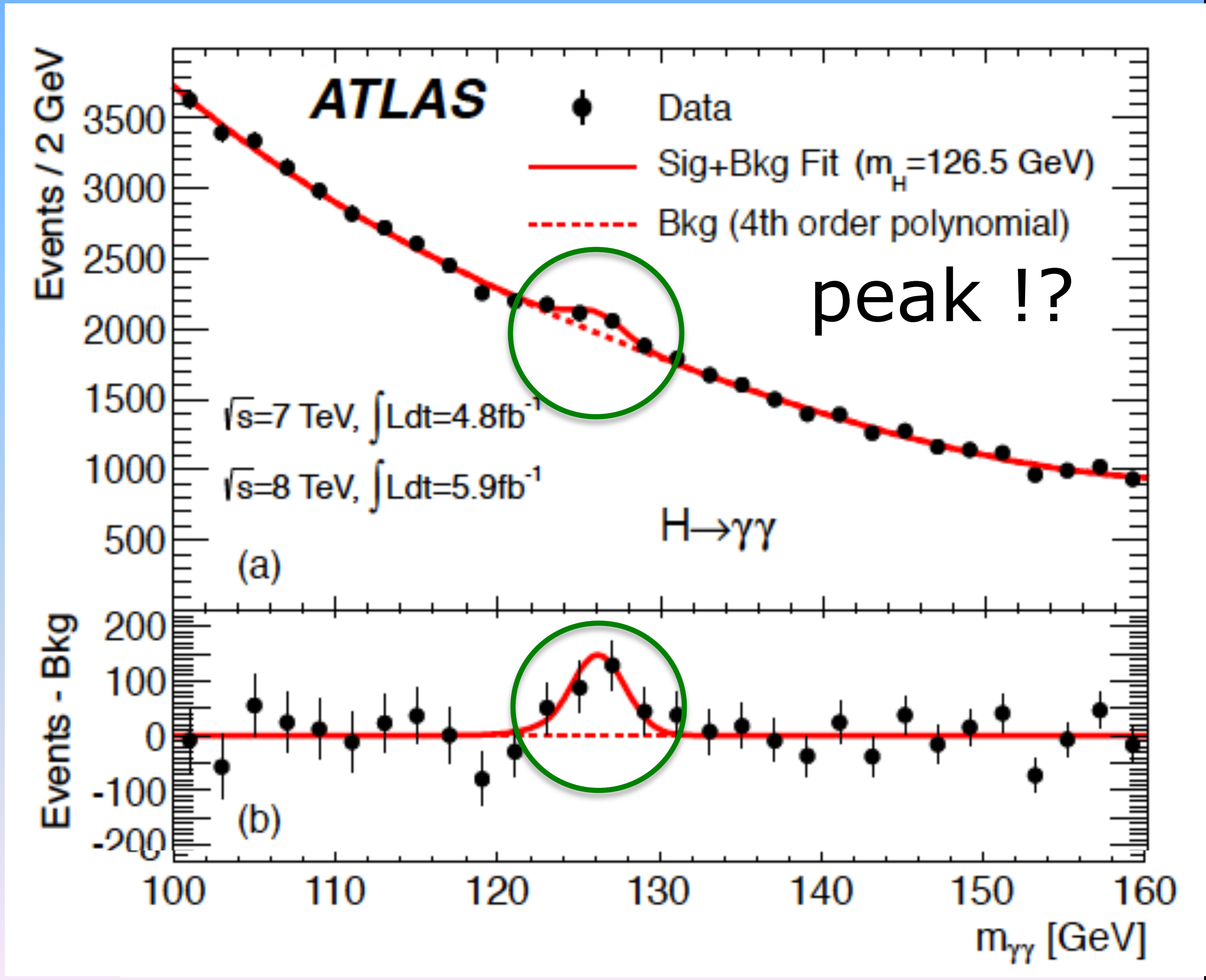
60 (Higgs → 4 lepton) events

'other'	52 events
with Higgs	68 events



Higgs → 2 photons





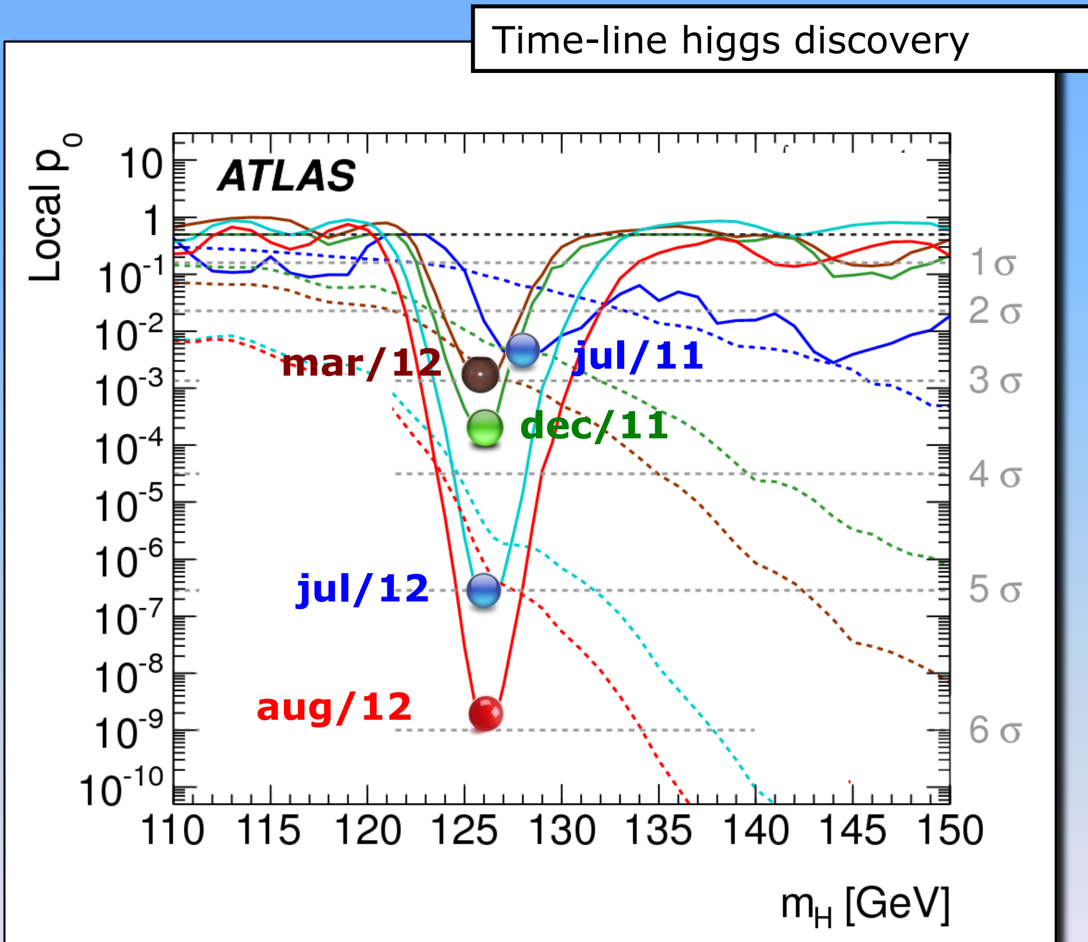
Interpretation of excess

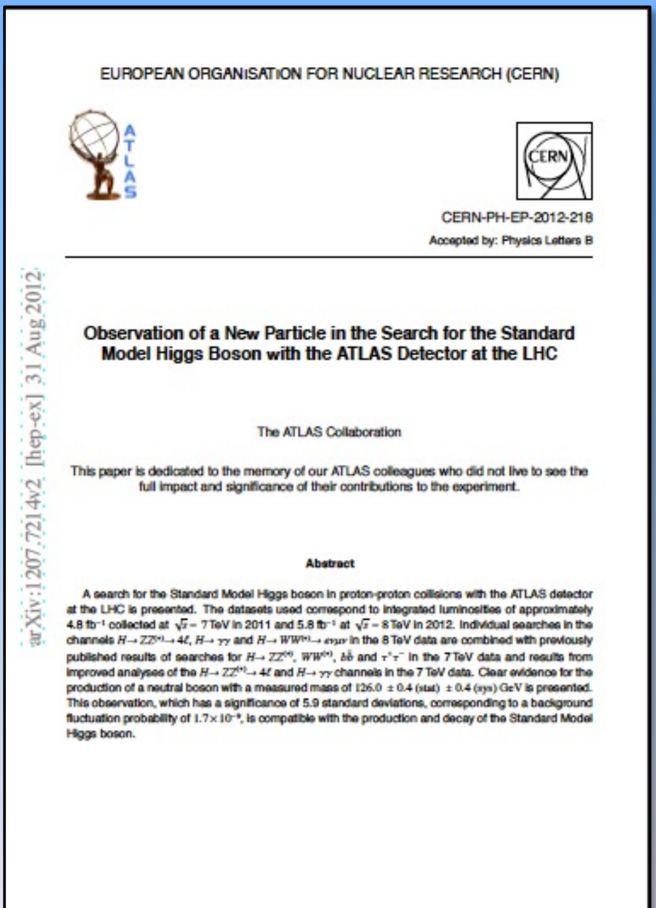
Claim discovery if:

Probability of observing excess smaller than 1 in 1 milion

Throwing 8 times 6 in a row

Discovery in slow-motion





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CERN-PH-EP-2012-218

Accepted by: Physics Letters B

arXiv:1207.7214v2 [hep-ex] 31 Aug 2012

Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC

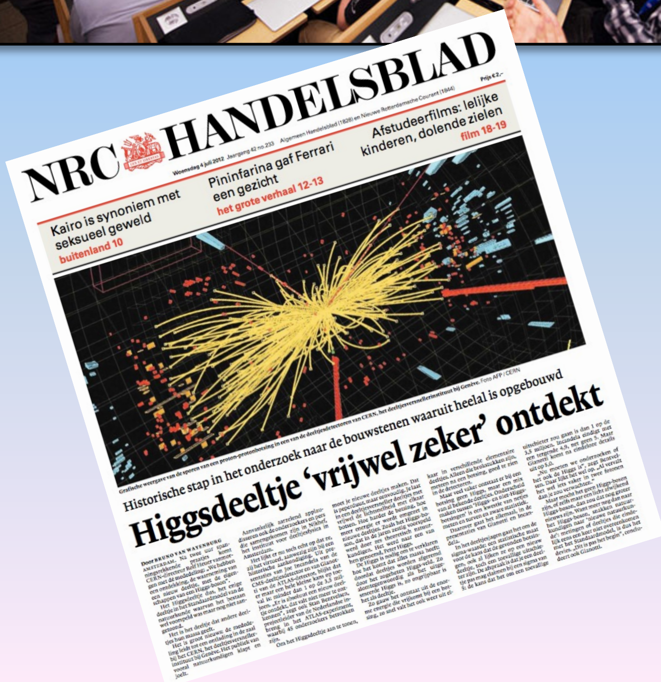
The ATLAS Collaboration

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

Abstract

A search for the Standard Model Higgs boson in proton-proton collisions with the ATLAS detector at the LHC is presented. The datasets used correspond to integrated luminosities of approximately 4.8 fb^{-1} collected at $\sqrt{s}$ = 7 TeV in 2011 and 5.8 fb^{-1} at $\sqrt{s}$ = 8 TeV in 2012. Individual searches in the channels $H \to ZZ^{(*)} \to 4\ell$, $H \to \gamma\gamma$ and $H \to WW^{(*)} \to e\nu\mu\nu$ in the 8 TeV data are combined with previously published results of searches for $H \to ZZ^{(*)}$, $WW^{(*)}$, $b\bar{b}$ and $\tau^+\tau^-$ in the 7 TeV data and results from improved analyses of the $H \to ZZ^{(*)} \to 4\ell$ and $H \to \gamma\gamma$ channels in the 7 TeV data. Clear evidence for the production of a neutral boson with a measured mass of 126.0 ± 0.4 (stat) ± 0.4 (sys) GeV is presented. This observation, which has a significance of 5.9 standard deviations, corresponding to a background fluctuation probability of 1.7×10^{-9}, is compatible with the production and decay of the Standard Model Higgs boson.

Discovery of Higgs particle on July 4, 2012


NRC HANDELSBLAD

Woensdag 4 juli 2012 Jaargang 42 no.233 Algemeen Handelsblad (1828) en Nieuwe Rotterdamsche Courant (1844)

Prijs € 2,-

Kairo is synoniem met seksueel geweld
buitenland 10

Pininfarina gaf Ferrari een gezicht
het grote verhaal 12-13

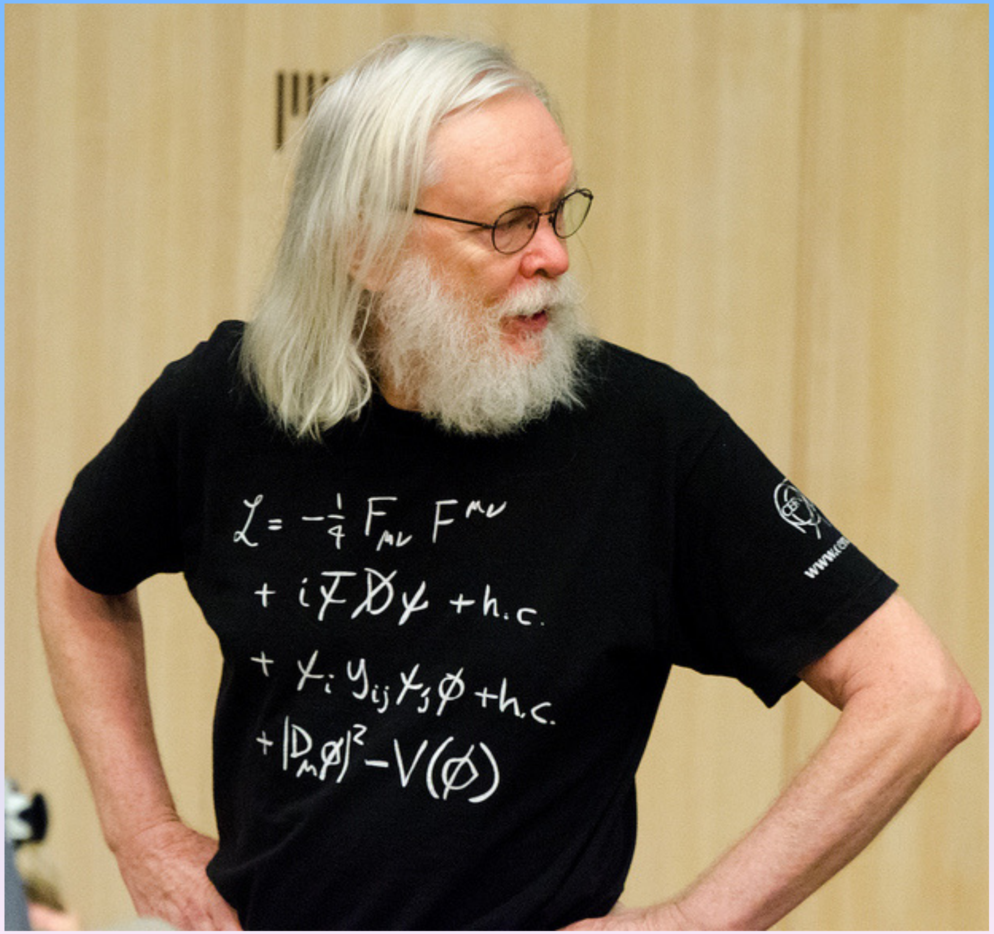
Afstudeerfilms: lelijke kinderen, dolende zielen
film 18-19

Grafische weergave van de sporen van een proton-protonbotsing in een van de deeltjesdetectoren van CERN, het deeltjesversnellerinstituut bij Genève. Foto AFP / CERN

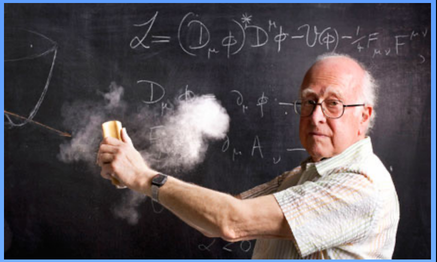
Historische stap in het onderzoek naar de bouwstenen waaruit heelal is opgebouwd

Higgsdeeltje ‘vrijwel zeker’ ontdekt

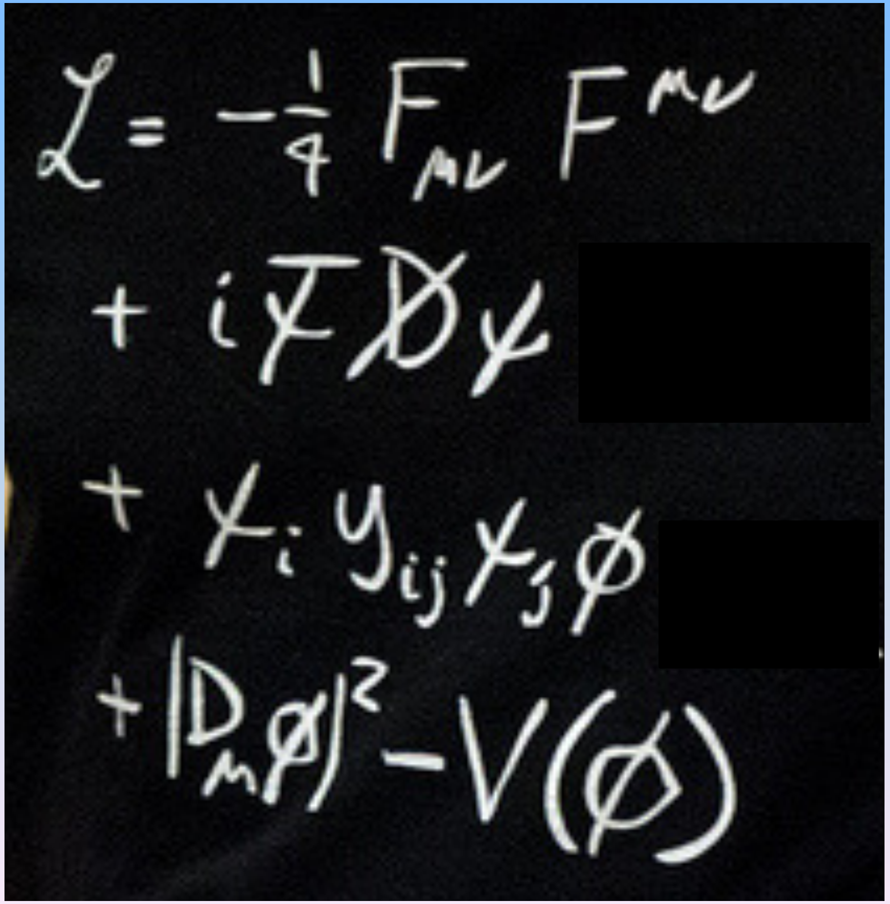
Why is Higgs so special?



Why is Higgs so special?



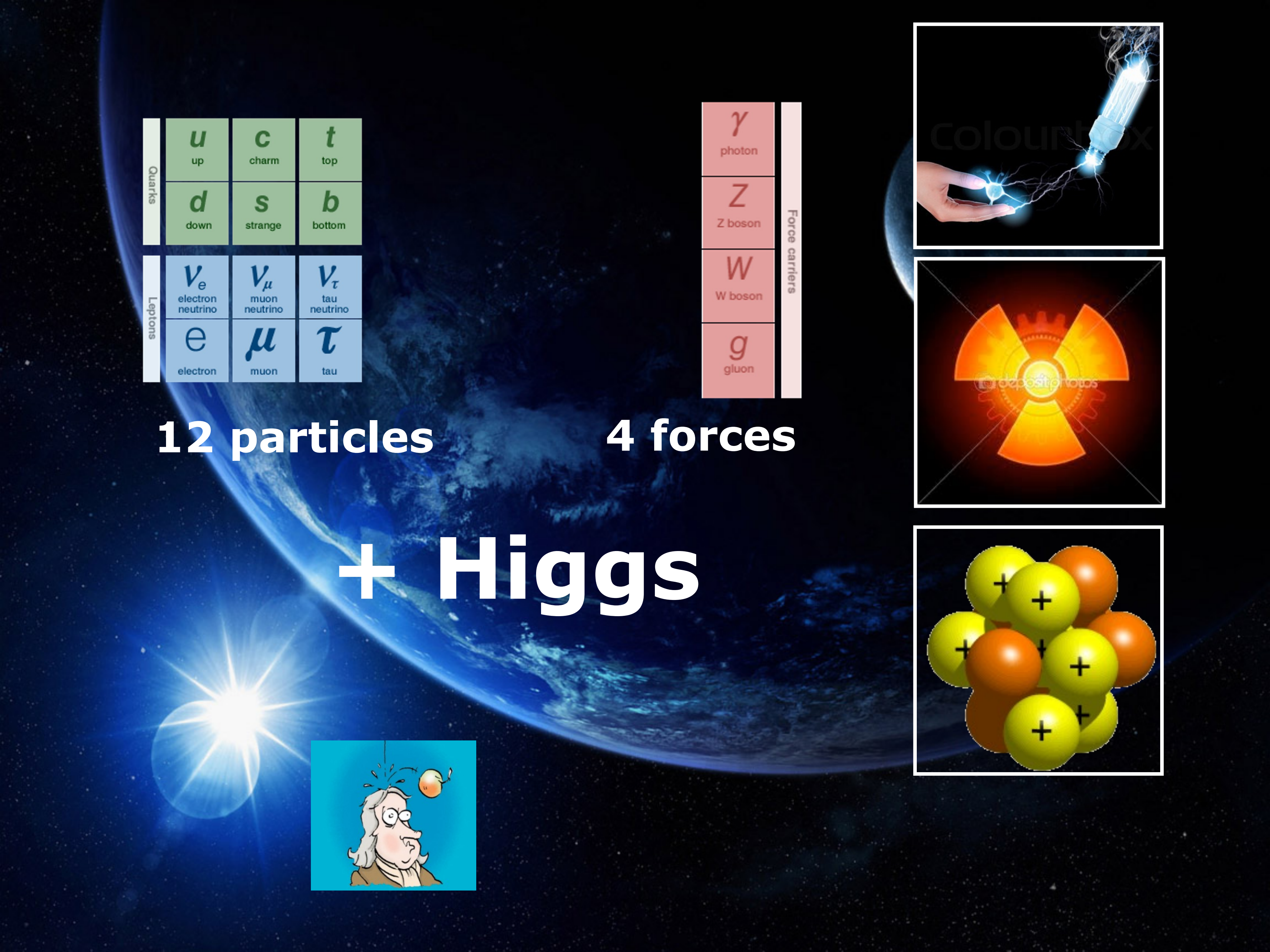
Higgs has unique role in world of elementary particles



ψ: "normal" particles

φ: Higgs

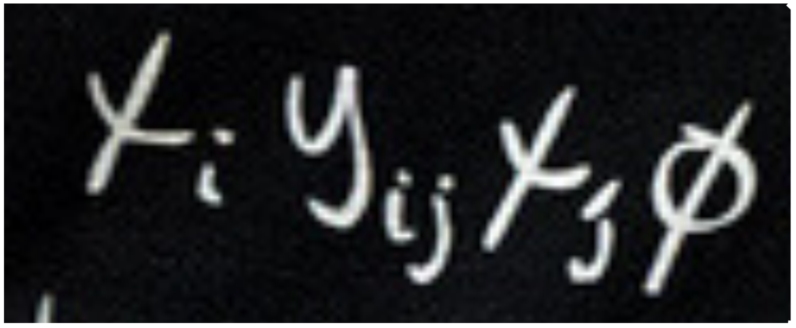
Half of T-shirt is about Higgs!

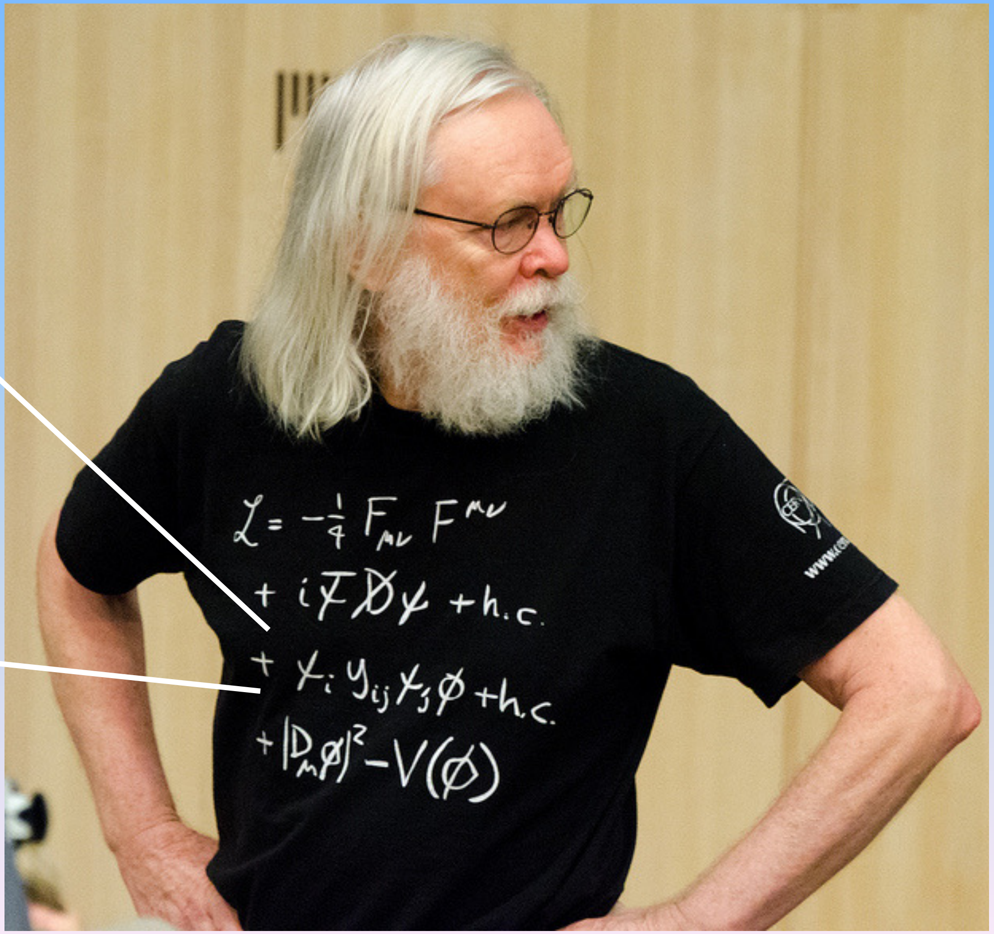


Quarks
u up
c charm
t top
d down
s strange
b bottom
Leptons
ν_e electron neutrino
ν_μ muon neutrino
ν_τ tau neutrino
e electron
μ muon
τ tau
12 particles
γ photon
Z Z boson
W W boson
g gluon
Force carriers
4 forces
+ Higgs

Higgs and LHCb?

m: ψψH

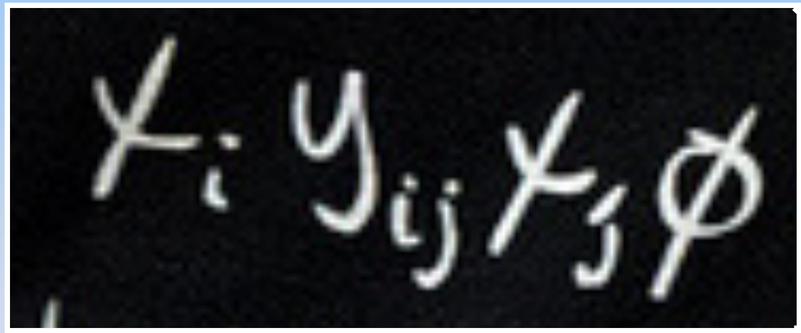


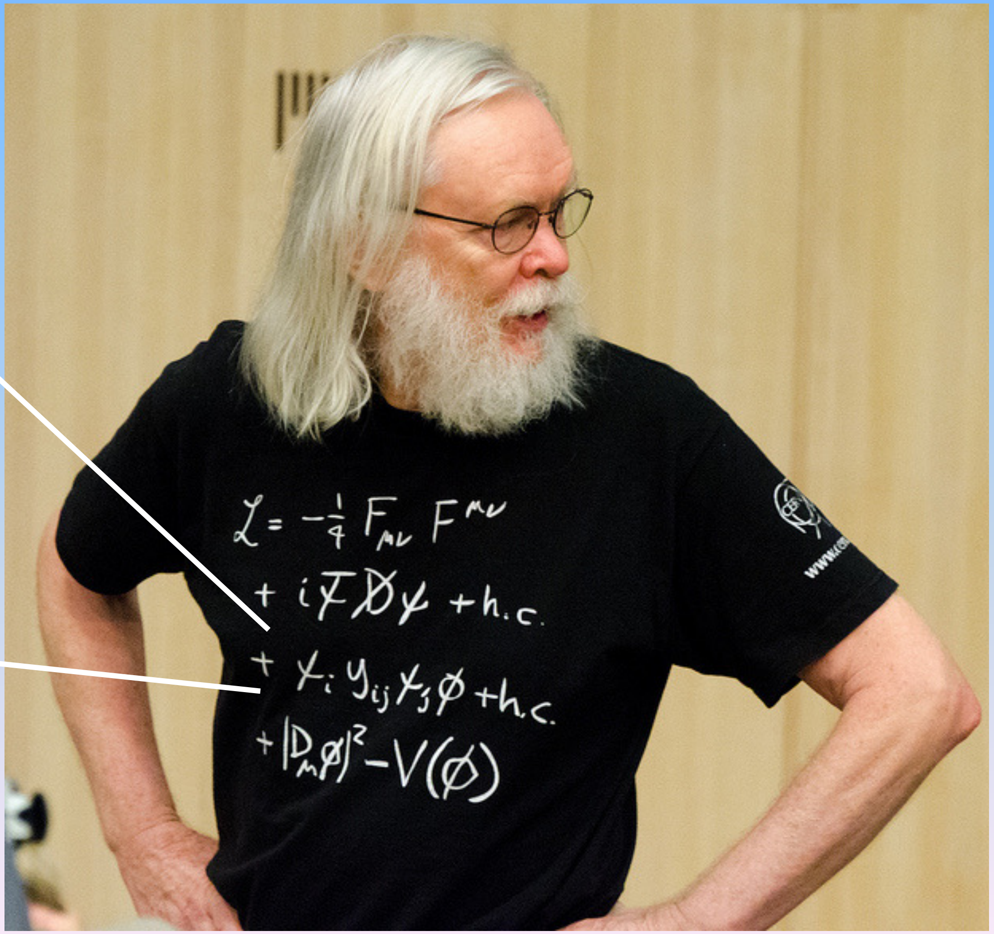


Higgs and LHCb?

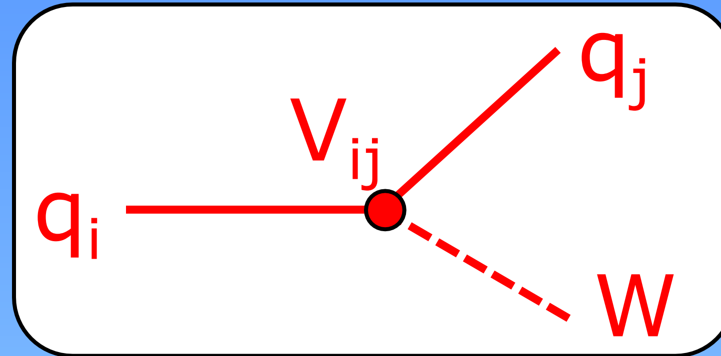
ψ: quarks

Y_{ij}: coupling between quarks i,j





Higgs and LHCb?



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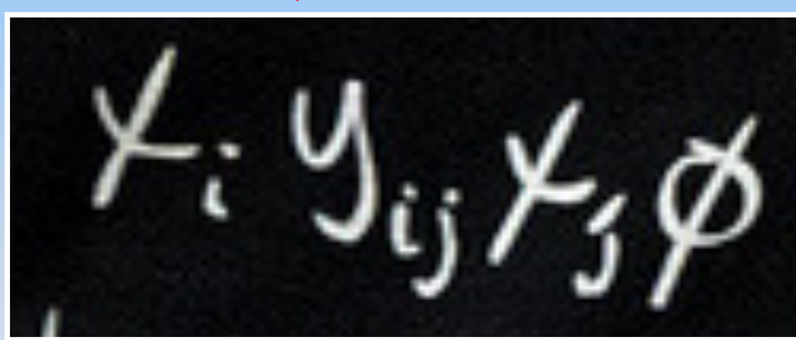
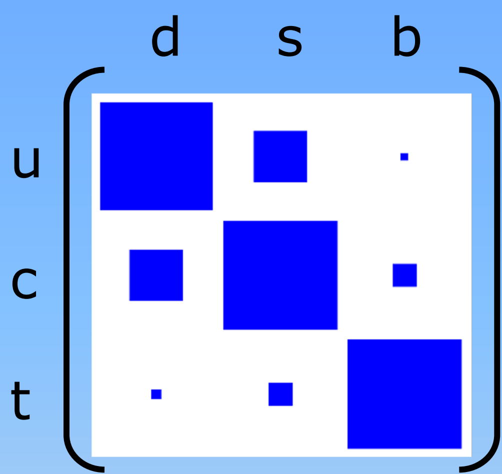
Y_{ij}: coupling between quarks i,j



Higgs and LHCb?

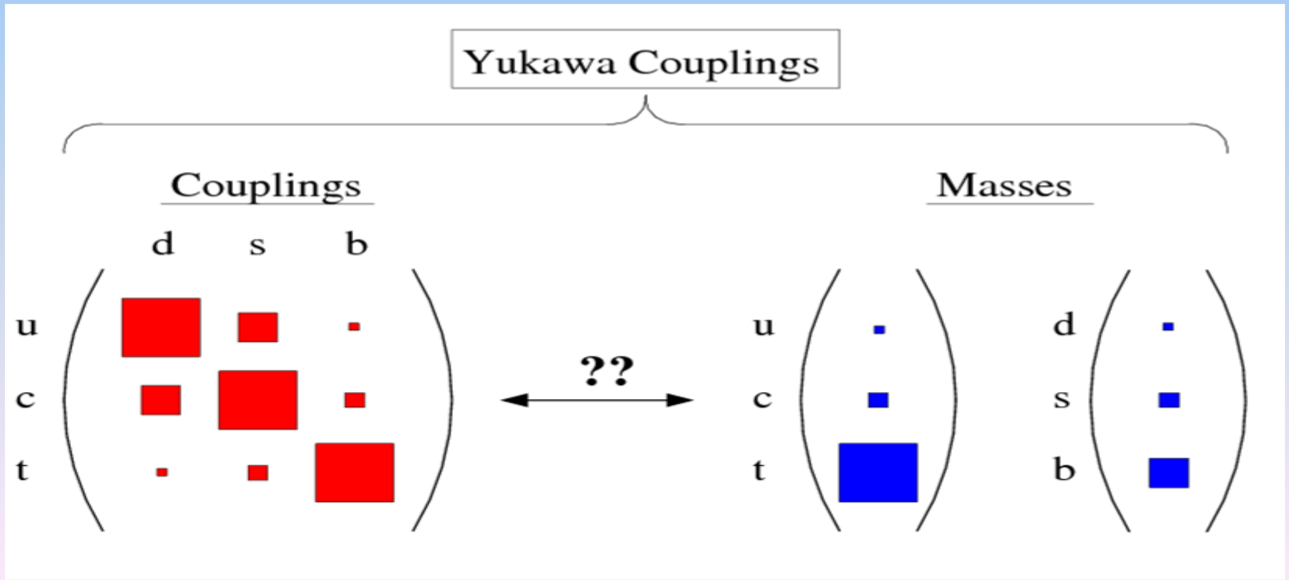
CKM magnitudes



Why the ranking in quark couplings?

Why the ranking in quark masses?

→ **Is there a connection?**



A few ‘small’ things:

1. Where did the anti-matter go?

2. 80% of all matter in the Universe is unknown
→ dark materie

3. Higgs boson and quark couplings?
(what is the connection) ?

- why does gravitaty not fit in SM, extra dimensions, why 3 families, fermions fundamental particles, supersymmetry, protons stable, quantisation electric charge, exploding quantum corrections, small neutrino masses, string theory, …

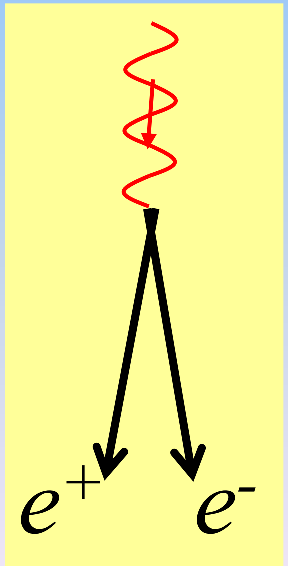
Einde

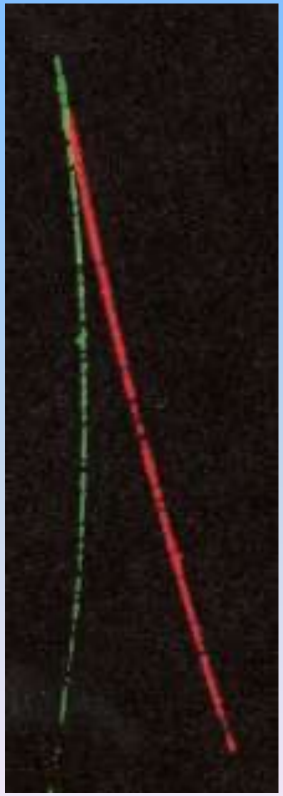
Higgs and the Universum

Higgs: Particle? Field?

<u>Particle</u>

Photon (light particle)



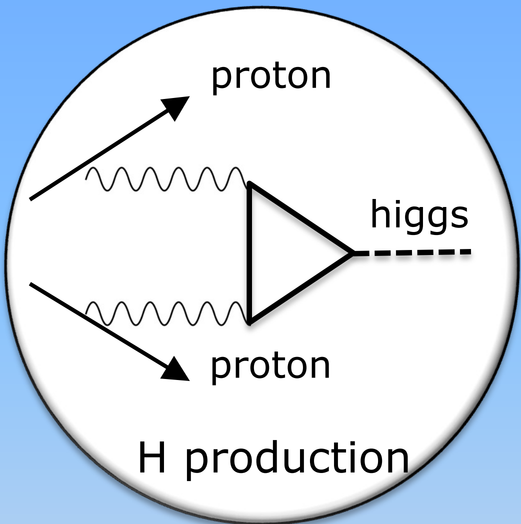


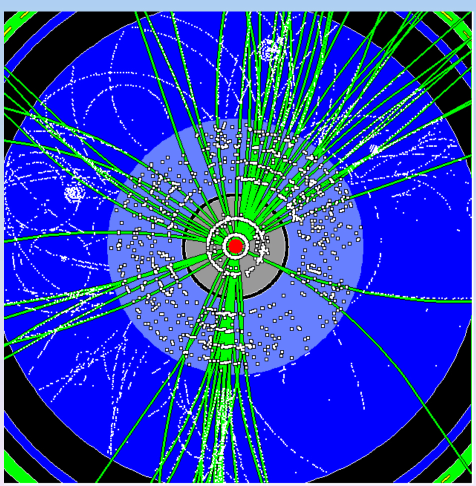
<u>Field</u>

Electrical field

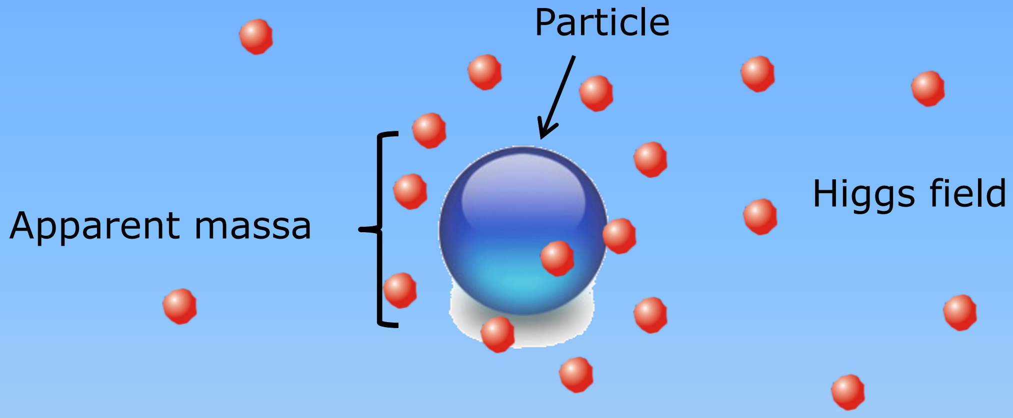
Why is the Higgs particle so special?

Particle





Field



As if the fish discovered the water he's in…

The Higgs field – can you see it?

The Higgs field is uniform – like the lake in this picture

Making a Higgs particle is like a ripple on the water

Theory of Higgs:

if the field exists, also

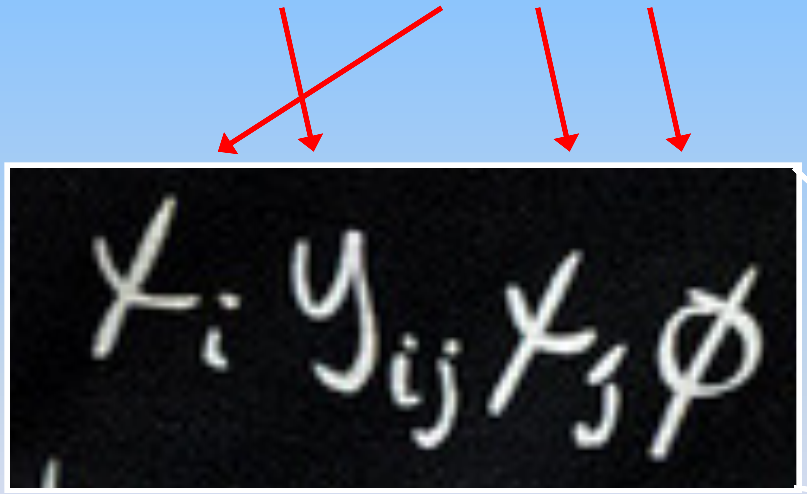
the particle exist

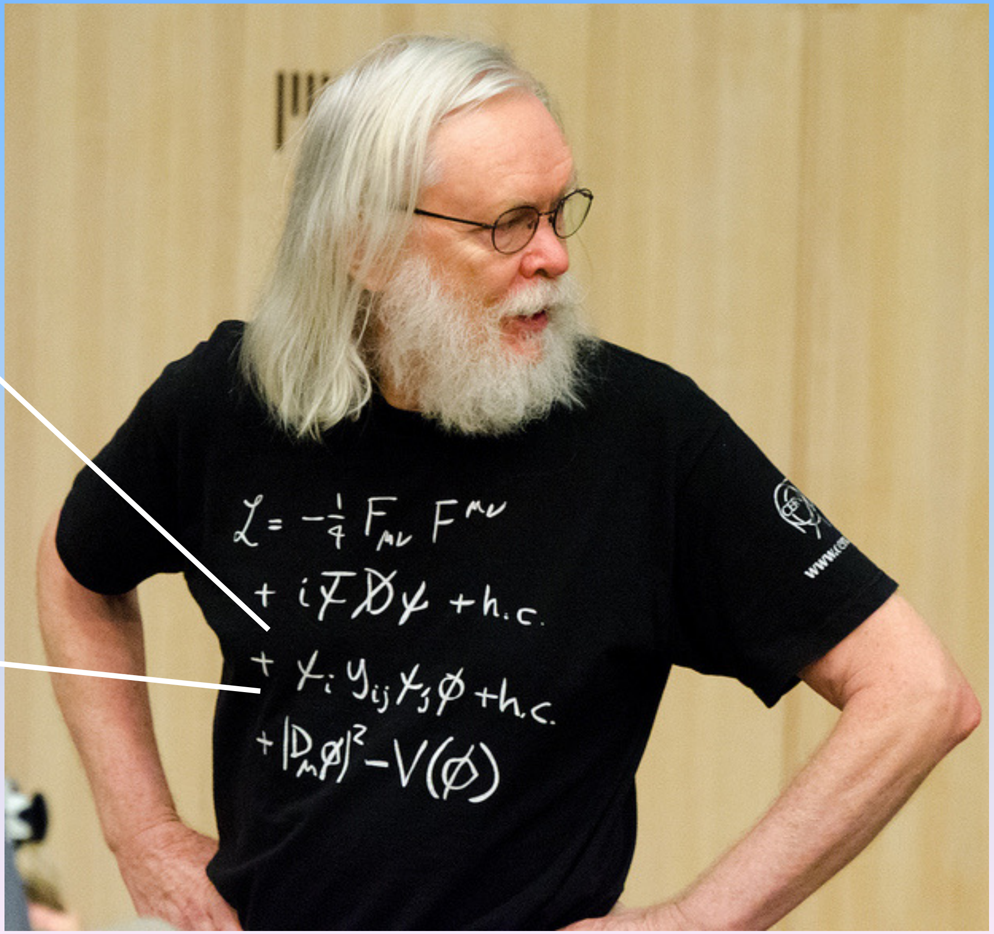
What is mass ?? Anno 1964

Mass of elementary particles is due to

“friction” of ubiquitous ‘Higgs field’

m: ψψH



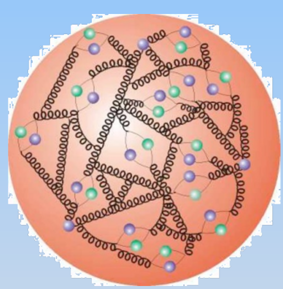


What is mass?

Mass of elementary particles is due to

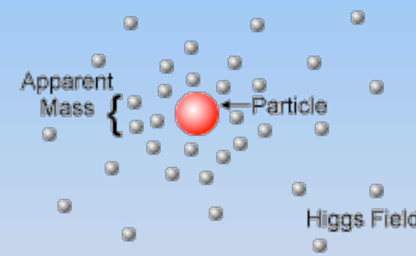
"friction" of ubiquitous 'Higgs field'

Einstein:
proton mass =
binding energy



Elementary particle
in empty space:
no rest-energy=
no mass

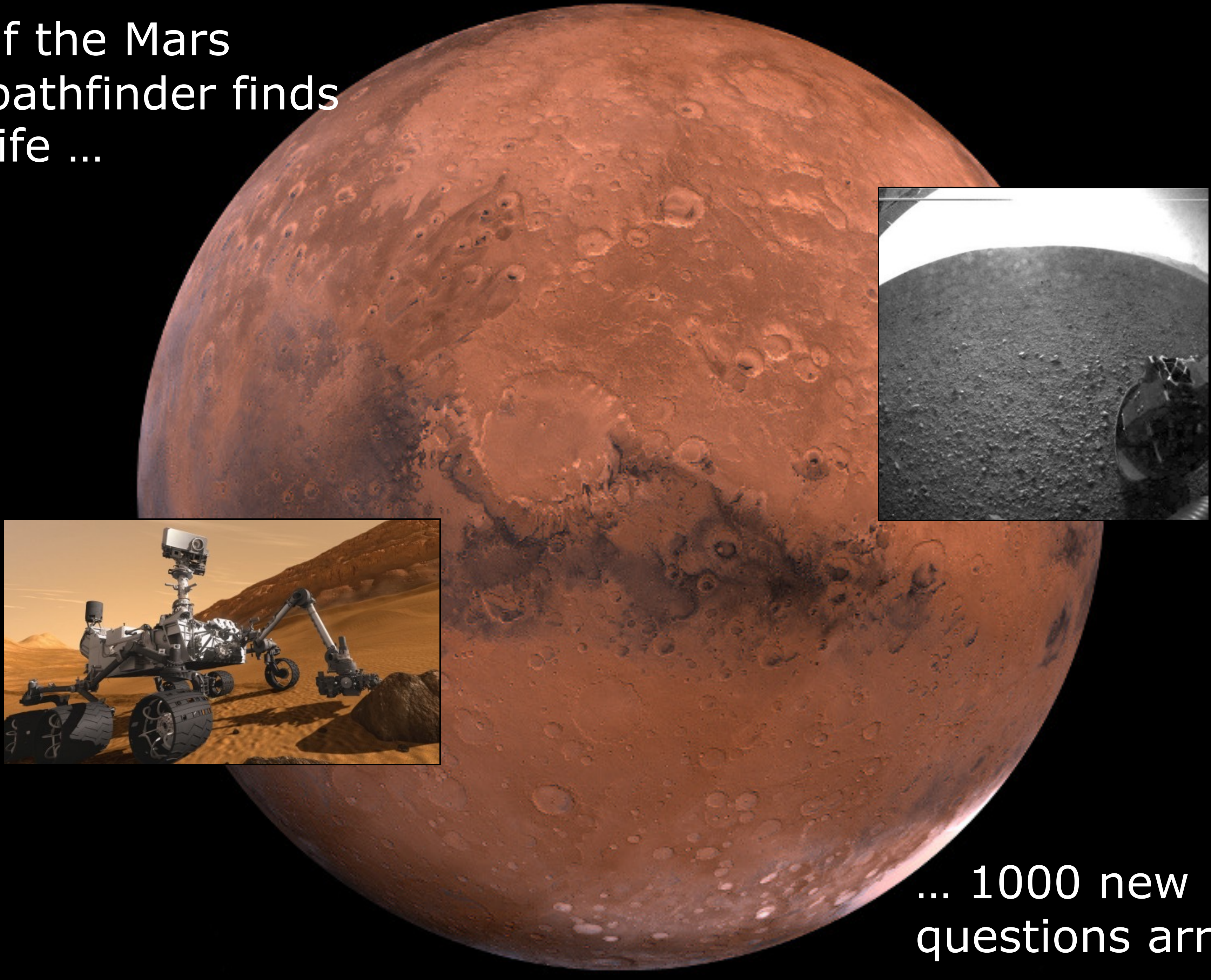
Elementary particle
in Higgs field:
rest energy =
interaction with Higgs field
= mass!



Revolutionary – with spectaculair consequences :

space is *not* empty, but filled with sort of 'ether'

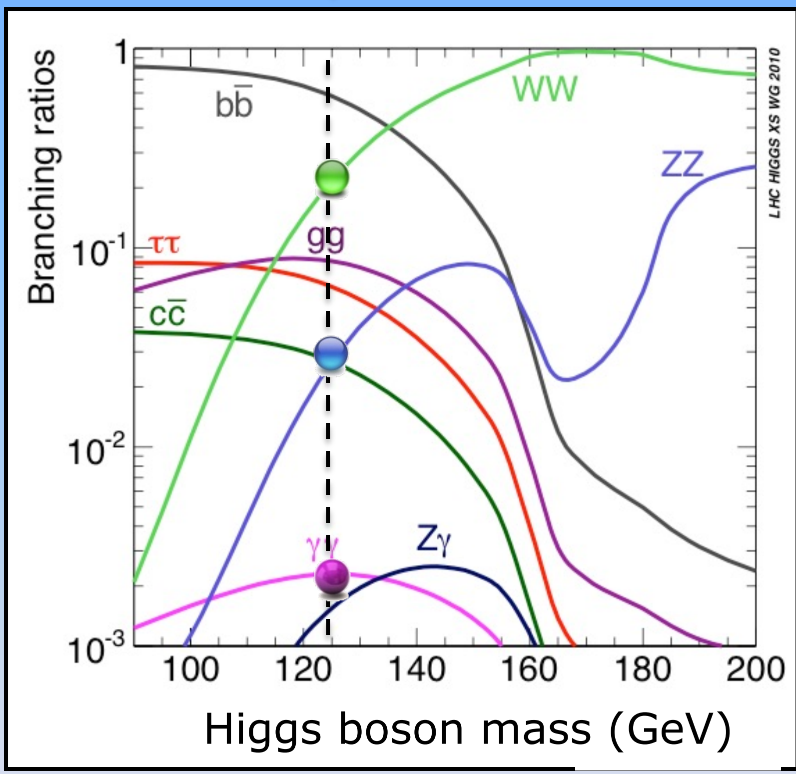
If the Mars pathfinder finds life …



… 1000 new questions arrise

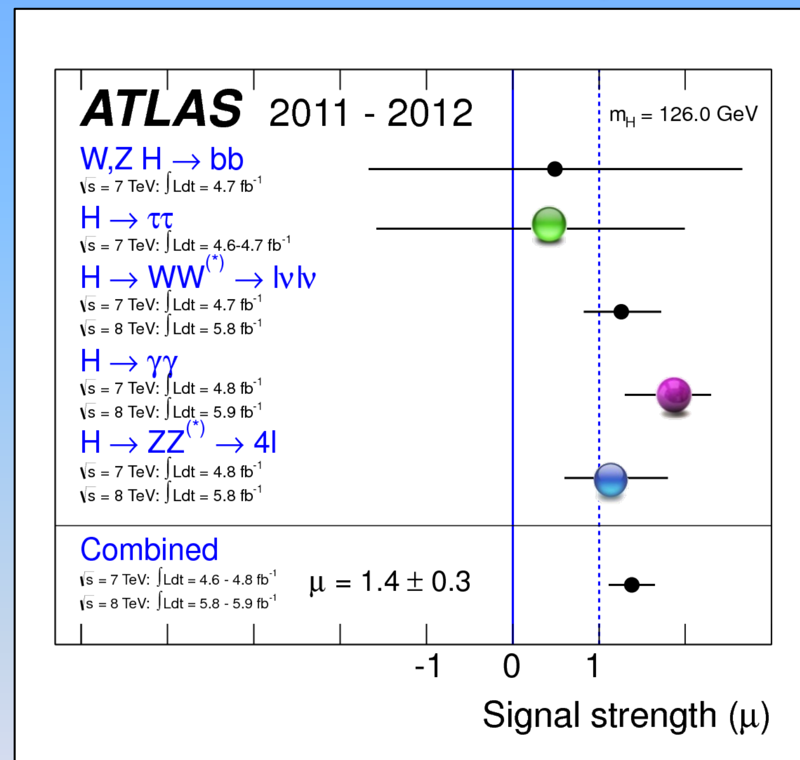
Higgs' properties as expected?

m_h=125 GeV ↓



prediction

Standard Model ↓



measurement

Higgs' properties as expected?

Are there more Higgs particles?

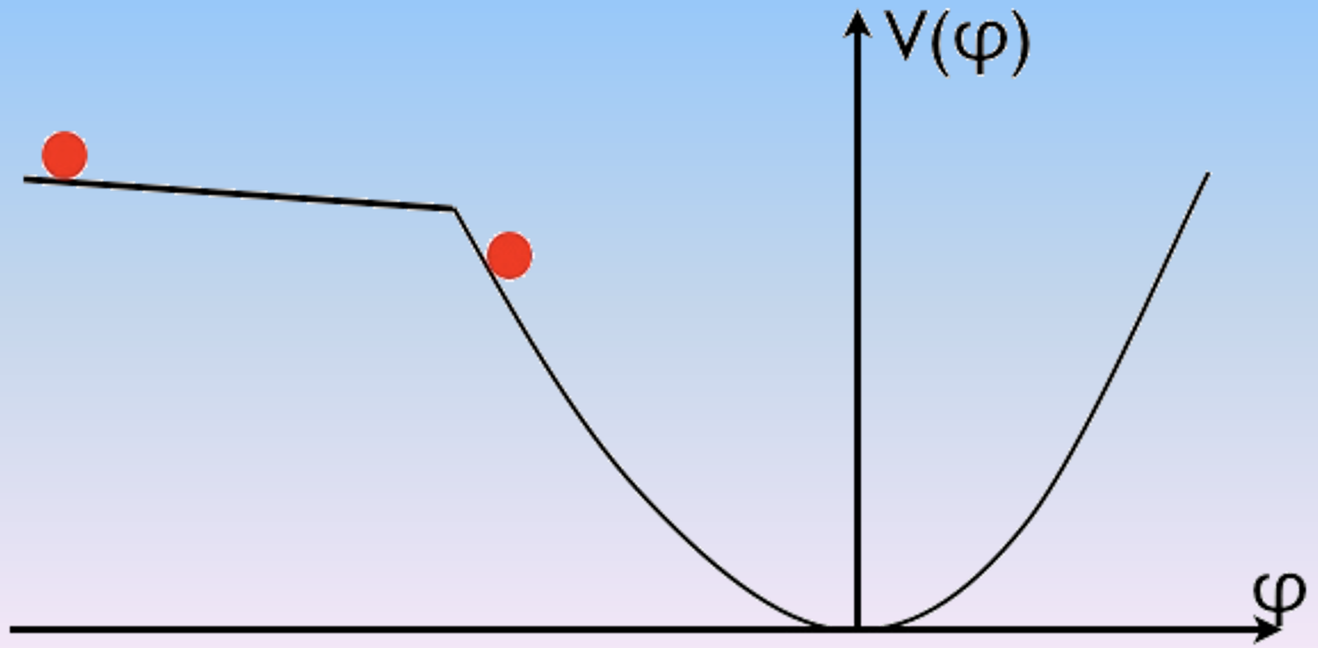
$$\mathcal{L}_{\text{susy}} = -\frac{g^2}{8}\left(H_u^\dagger \sigma^a H_u + H_d^\dagger \sigma^a H_d\right)^2 - \frac{g'^2}{8}\left(H_u^\dagger H_u - H_d^\dagger H_d\right)^2$$
$$+ \lambda_{ij}^u H_u^T \epsilon \bar{u}_i q_j - \lambda_{ij}^d H_d^T \epsilon \bar{d}_i q_j - \lambda_{ij}^e H_e^T \epsilon \bar{e}_i \ell_j$$
$$- \frac{H_u^\dagger}{\sqrt{2}}\left(g\sigma^a \tilde{W}^a + g'\tilde{B}\right)\tilde{H}_u - \frac{H_d^\dagger}{\sqrt{2}}\left(g\sigma^a \tilde{W}^a - g'\tilde{B}\right)\tilde{H}_d + \text{h.c.}$$

One step further…

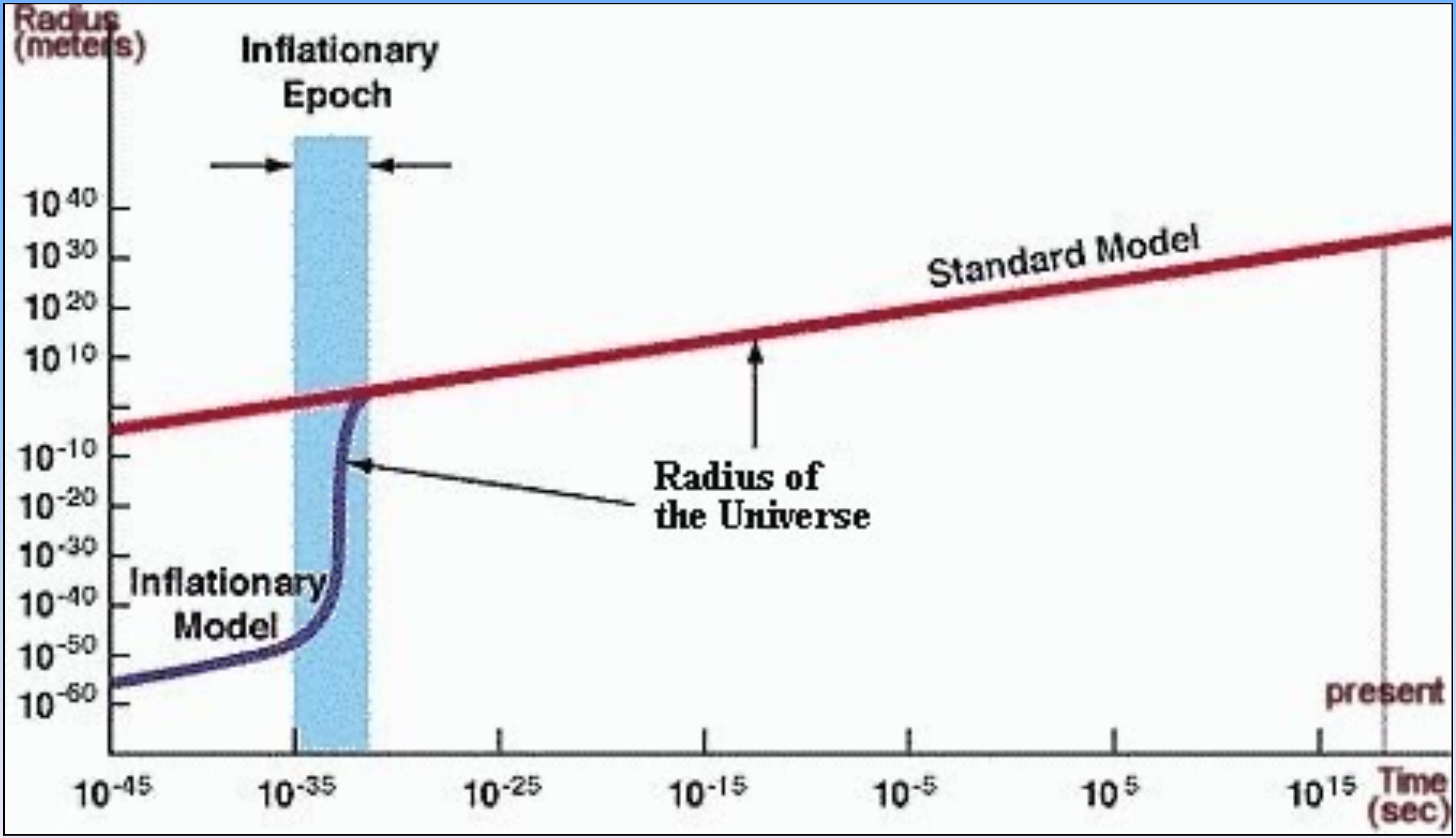
Another field: the Big Bang

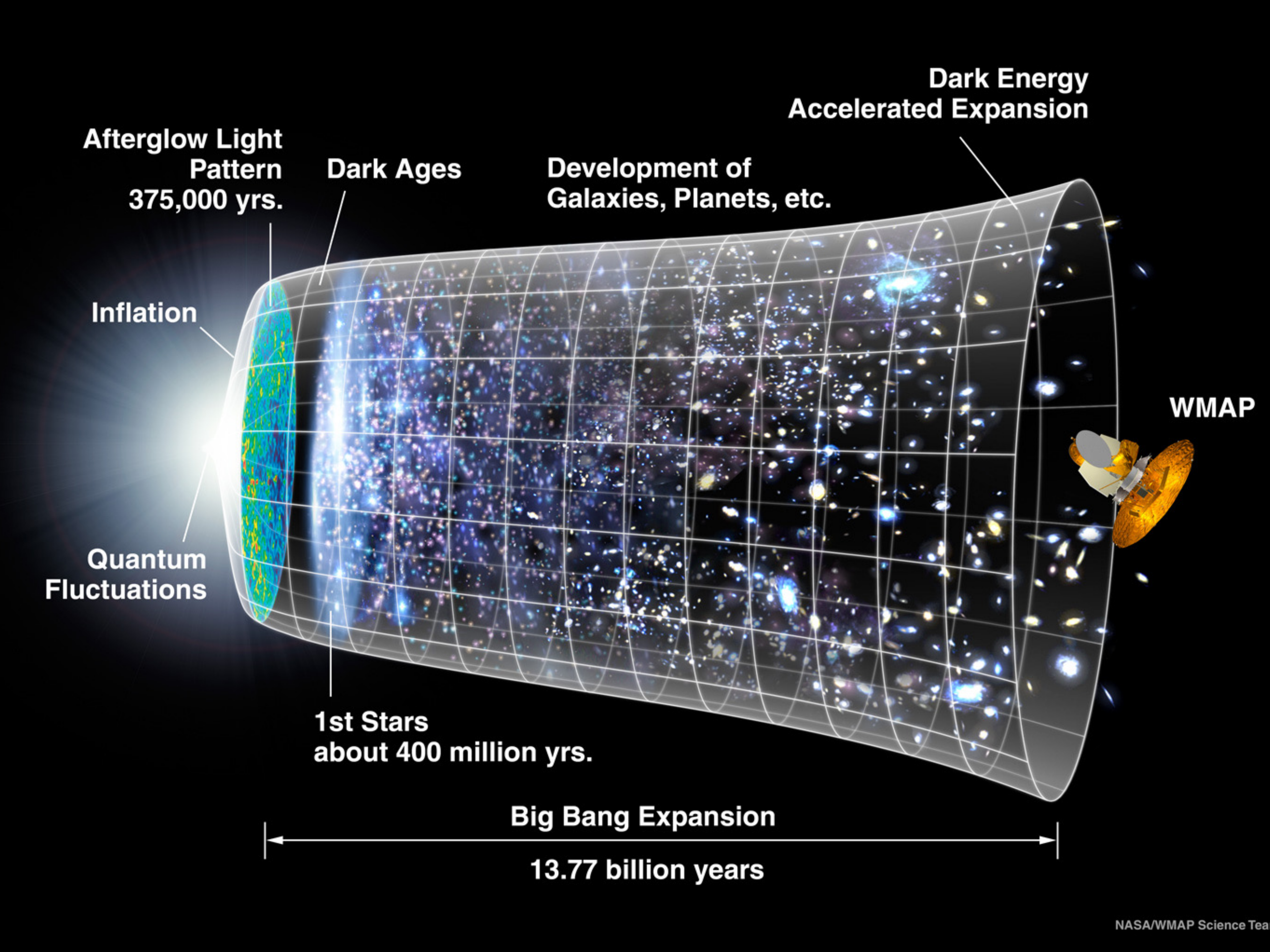
One of Higgs' properties match that of another field…

The *inflaton* that inflated the Universe between 10^{-33} and 10^{-32} seconds after the Big Bang



Another field: the Big Bang




Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years
NASA/WMAP Science Tea

Higgs:

1. Higgs particle discovered in Geneve
2. Universe filled with the Higgs field
3. Higgs properties as expected?

A few 'small' things:

4 Where did the anti-matter go?

5 80% of all matter in the Universe is unknown
→ dark materie

6 Higgs boson and quark couplings?
(what is the connection) ?

- why does gravitaty not fit in SM, extra dimensions, why 3 families, fermions fundamental particles, supersymmetry, protons stable, quantisation electric charge, exploding quantum corrections, small neutrino masses, string theory, …

EINDE

What is the purpose of this research?

Fundamental research

- Leads to surprises,
  - Sometimes even useful…
  - But always unknown

"Infinite amount of applied research on candles, would never have brought us electric light."

What is the purpose of this research?

Fundamental research

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  - Sometimes even useful…
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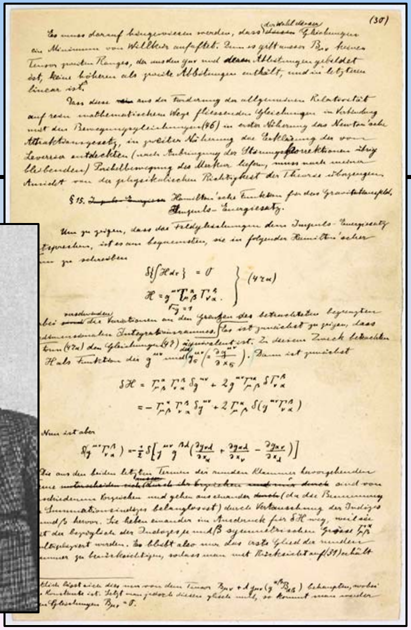


"Without theory of relativity, GPS would be wrong by 10km/day !"

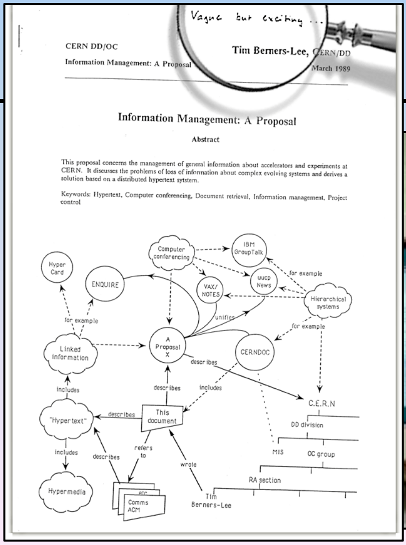
What is the purpose of this research?

Fundamental research

- Brings useful spin-off
  - Medical applications
  - Internet
  - Educating researchers for society (Philips, ASML, etc, etc)

PET scan

www



Vague but exciting ...

CERN DD/OC

Information Management: A Proposal

Tim Berners-Lee, CERN/DD

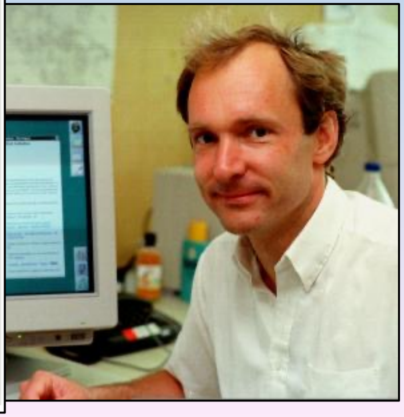
March 1989

Information Management: A Proposal

Abstract

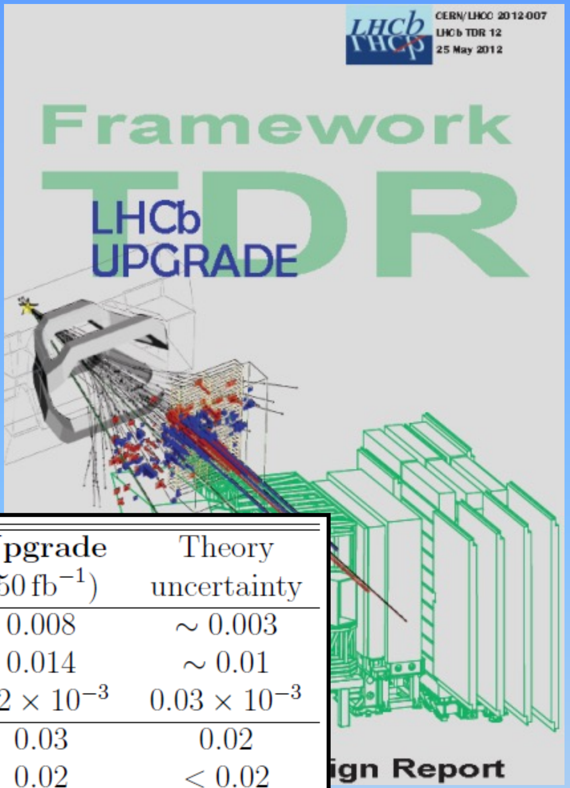
This proposal concerns the management of general information about accelerators and experiments at CERN. It discusses the problems of loss of information about complex evolving systems and derives a solution based on a distributed hypertext sytstem.

Keywords: Hypertext, Computer conferencing, Document retrieval, Information management, Project control



LHCb: How further?

- More precise! → Upgrade (2018)



Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\text{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s$ ($B_s^0 \to J/\psi\ \phi$)	0.10 [30]	0.025	0.008	~ 0.003
	$2\beta_s$ ($B_s^0 \to J/\psi\ f_0(980)$)	0.17 [32]	0.045	0.014	~ 0.01
	a_{sl}^s	6.4×10^{-3} [63]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguins	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\text{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\text{eff}}(B^0 \to \phi K_S^0)$	0.17 [63]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\text{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguins	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.08 [64]	0.025	0.008	0.02
	$s_0\ A_{\text{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [64]	6 %	2 %	7 %
	$A_{\text{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.25 [9]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [29]	8 %	2.5 %	~ 10 %
Higgs penguins	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [4]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	~ 10–$12°$ [40, 41]	4°	0.9°	negligible
	$\gamma\ (B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	$\beta\ (B^0 \to J/\psi\ K_S^0)$	0.8° [63]	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [63]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [8]	0.65×10^{-3}	0.12×10^{-3}	–

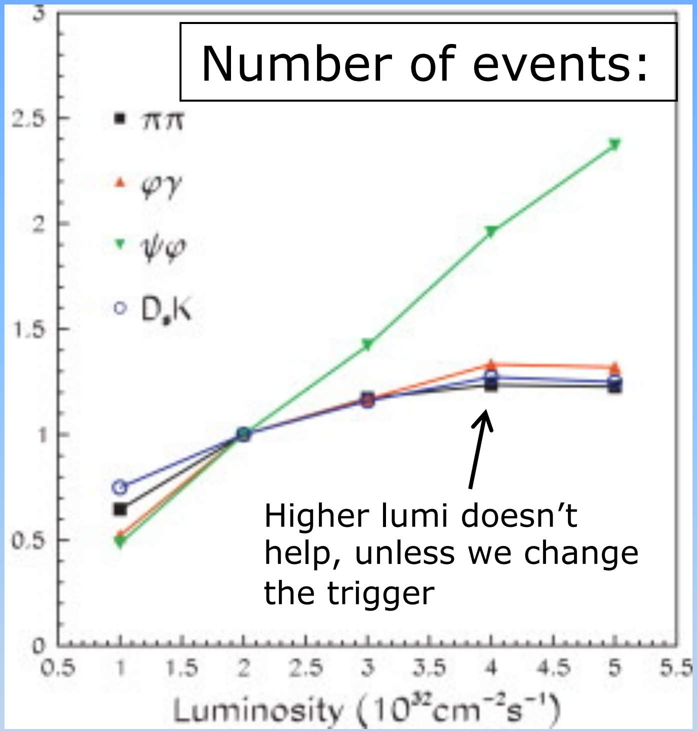
LHCb: Upgrade - Trigger

- Precise → More luminosity

1) More luminosity → ~~Higher trigger rate~~

2) More luminosity → Higher threshold

- ~~Higher threshold → Less events ...~~



<u>Solution:</u>

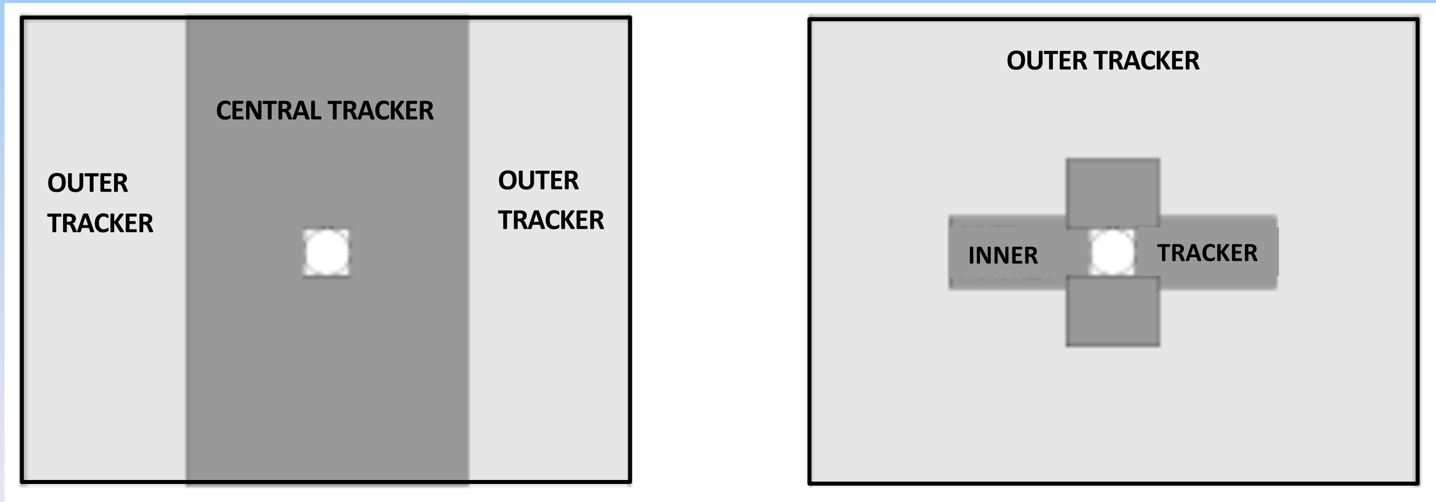
Smarter trigger → *all* events to CPU farm:

➢ Readout @40 MHz, not 1 MHz …

LHCb: Upgrade - Detectors

- Precise → More luminosity
- More luminosity → Higher particle rate
- Higher particle rate → Occupancy too large in Outer Tracker

➢ <u>2 options:</u>



1) Inner Tracker becomes Scintil. Fiber, Outer Tracker becomes <u>less</u>

2) Inner Tracker becomes bigger, Outer Tracker becomes <u>smaller</u>